GRAY'S ANATOMY

CARDIOVASCULAR SYSTEM

Section Editor: Giorgio Gabella

With contributions from Professor Robert Anderson, MD, Mr Julian Dussek FRCS, Dr Susan Evans, PhD, Mr Adrian Marston, FRCS and Dr Marta Perry, MUDr, PhD. Professor Anderson was responsible for the revision of the Heart and contributed all the colour photographs of the heart and the diagrams 10.22, 43, 44, 57, 62, 63, 64. Dr Evans revised the General Introduction on the evolutionary aspects of cardiac morphology. The section on the pulse and central venous access were prepared by Mr Julian Dussek. Mr Marston advised on arteries and veins of the abdomen 10.116, 117, 120, 125–127, and Dr Perry wrote the essay on leucocyte-endothelial cell interaction.

BLOOD VESSELS

INTRODUCTION

Movement and exchange of materials in the watery medium of living tissues takes place by diffusion, most commonly along chemical gradients. A vital requirement in large and complex organisms, however, is a fast, widespread, high-capacity system for continuously transporting to and from every single part of the body a large number of specific components, ranging from ions and small molecules to whole cells. This is the main function served by the vascular or circulatory system.

- Blood (see section 9) is the vehicle which maintains a vast chemical traffic through the body, moving hormones, oxygen, nutrients, antibodies, catabolites, red and white blood cells, as well as infestants and toxic compounds. In addition, in ectotherms, blood redistributes and disperses heat, and, because of the pulse pressure, it also has mechanical effects, such as maintaining turgidity of tissues and counteracting certain effects of gravity.
- The circulatory system is fast and has high capacity, for several reasons: because of the rheological properties of blood, because of the large volume of blood, and because of the mechanical properties of the heart and muscular arteries.
- The circulatory system is made up of the heart—a central pump and the main motor of the system—and by a vast array of tubes which lead away from the heart (as arteries) and carry the blood to the 'periphery' of the body; at the periphery, that is within organs and tissues, the tubes loop back and (as veins) reach the heart again where the blood eventually returns.

Schematically, one can envisage the vascular system as made up of long loops which are centred on the heart (at which level both arteries and veins are largest) and are much reduced in size and extremely arborized at the periphery (capillaries) (10.1). There are, in fact, not one but two such loops, because the heart is a **pair** of muscular pumps, one feeding a minor loop (pulmonary circulation), which serves the lungs, the other feeding a major loop (systemic circulation), which serves all the rest of the body. The two loops are also referred to as the *greater* and *lesser circle*.

With limited exceptions, which will be discussed in due course, each loop is a closed system of tubes, so that blood per se does not usually leave the circulation. As William Harvey discovered in the seventeenth century, blood is pumped away from the heart but it all returns to the heart after circulation through the body. Arteries are the vessels that carry the blood away from the heart, and veins are the vessels that carry it back to the heart.

From the centre to the periphery, the vascular tree shows three main changes:

- The arteries increase in number by repeated division and by the issuing of side branches, in both the systemic and the pulmonary circulation.
- The arteries also decrease in diameter, although not to the same extent as they increase in number, so that a notional cross-section of all the vessels at a given distance will have the greatest area the furthest away it is from the heart. As a result, blood flow is faster near the heart than at the periphery.
- Among other structural changes, the wall of the arteries decreases in thickness, although this is not as substantial as the reduction of the vessel diameter. In consequence, in the smallest arteries (arterioles) the thickness of the wall represents about half the outer radius of the vessel, whereas in a large vessel it represents between one-fifteenth and one-fifth. For example, in the thoracic aorta the radius is about 17 mm and the wall thickness 1.1 mm (Wolinsky & Glagov 1967a). From a functional viewpoint, while **size** is a fundamental parameter of a blood vessel, **position** of the vessel in the body and **structure of the vessel wall** are also very important characteristics, which dictate the properties of the vessel. Furthermore, whereas microcirculation vessels are remarkably similar in animal species of very different body size, equivalent large vessels vary greatly not only in size but also in wall thickness in mammals of different body size—an important consideration when
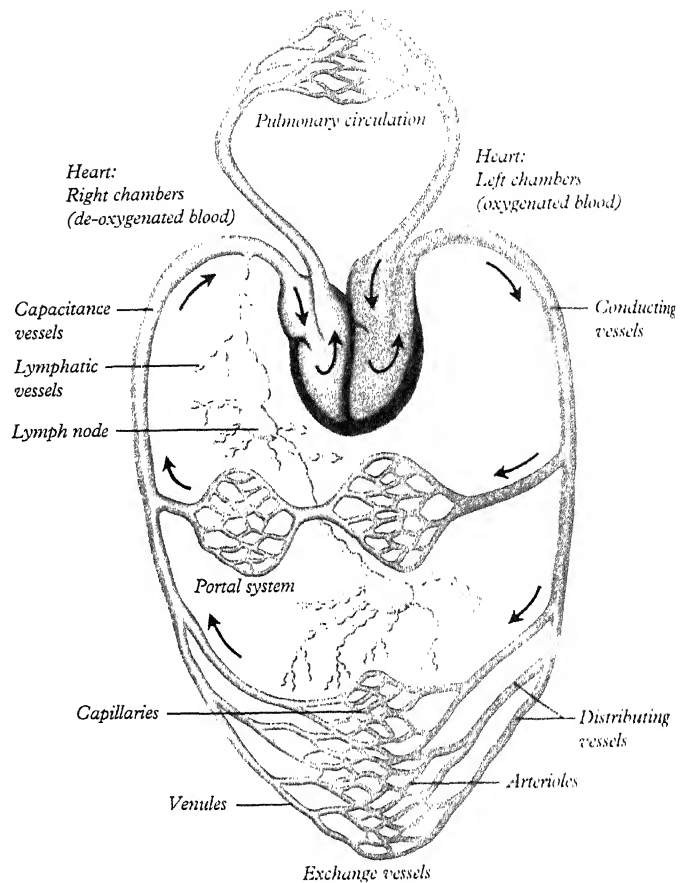
10.1 Diagrammatic drawing of the cardiovascular and lymphatic system. The nomenclature of the main vessel types is indicated; in red are the vessels carrying oxygenated blood, in blue those carrying un-oxygenated blood and in yellow the lymphatic structures.

data obtained on laboratory animals are extrapolated to man. As a first approximation, comparative studies show that in corresponding large arteries, the ratio between inner diameter and wall thickness is constant and is independent of body size (Caro et al 1978).

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VESSEL NUMBER

The aorta, the single systemic artery emerging from the heart, gives origin by successive branching to hundreds of arteries of progressively smaller calibre; by further branching these produce about 4×10^6 arterioles and four times as many capillaries. A similar number of venules converge onto each other forming a progressively smaller number of veins of increasingly larger size; eventually, two veins only, which are also the largest of the body, the superior and the inferior vena cava, open into the heart from the systemic circulation. A similar pattern is found in the pulmonary circulation (lesser circle). In the lesser circle, however, the vascular loop is shorter and has therefore fewer branching points; consequently, the number of vessels is smaller than in the greater circle.

VESSEL SIZE

At the emergence from the heart the aorta of an adult man has an

outer diameter of about 30 mm (sectional area of nearly $7 cm^2$). The diameter decreases along the arterial tree until it is as little as $10 \mu m$ in arterioles (sectional area of about $80 \mu m^2$) (Rothe 1983). However, given the enormous number of arterioles, the total cross-sectional area at this level is about $150 cm^2$, more than 200 times larger than at the level of the aorta (Wiedeman et al 1976); a further increase of the extent of the vascular bed takes place at the level of the capillaries and venules. In a 13-kg dog, the aorta had a cross-sectional area of $0.8 cm^2$ and the capillaries (estimated at 1.2×10^9) had a total cross-sectional area of $600 cm^2$ (Green 1950). Veins leading back to the heart grow progressively larger and fewer in number. As with the arteries, a cross-sectional area of all veins at a given level is smaller the nearer this is to the heart. Veins are a little larger than the corresponding arteries. The reduction in diameter along the vascular tree occurs when a vessel divides or issues collateral branches; in the absence of branches, the shape of a segment of any vessel is not a truncated cone but a cylinder.

The size of the vessels increases during development, while there are substantial changes in the structure of their wall. In old age, vessels generally become enlarged. In animal species, the size of comparable vessels is related to body size; so, while in a mouse the ascending aorta measures less than 2 mm in diameter, the same vessel in a blue whale measures over 30 cm, large enough for a human baby to swim through. In spite of these enormous differences in size there are no qualitative differences in the structure of the constitutive materials: similar types of cell and of extracellular material are found in corresponding vessels ranging in linear size over more than three orders of magnitude.

BRANCHING PATTERNS

When an artery divides into two branches of roughly equal size, these are called terminal branches, as that artery ceases to exist at this point. Branches issued along the course of an artery, before its termination, are usually of smaller size than terminal branches and are called collateral (or side) branches.

The angle of branching is related to the calibre of the vessels and it conforms to theoretical predictions based on the principle of minimum work (namely, in this context, the highest efficiency in blood flow) or the minimum 'cost' of the bifurcation (Woldenberg & Horsfield 1986), although there are many exceptions.

The *total cross-sectional area* of the daughter vessels is invariably greater than the cross-sectional area of the parent vessel. For example, the terminal portion of the abdominal aorta has an internal diameter of 13.8 mm, while each of the common iliac arteries has an internal diameter of about 9.7 mm, so that the bifurcation produces a 1.5-fold increase in total cross-sectional area. It has been calculated that vessels arising by equal bifurcation have a diameter 0.76 of that of the parent vessel (Green 1950).

ANASTOMOSIS

Arteries can be joined to each other by anastomosis, which makes them able to feed each other's territory. An *end-to-end anastomosis* occurs when two arteries open directly into each other (for example, the vaginal and the ovarian artery, the right and the left gastroepiploic arteries, the ulnar artery and the superficial palmar branch of the radial artery). Anastomosis by *convergence* occurs when two arteries converge and merge, as in the case of the vertebral arteries forming the basilar artery. A *transversal* anastomosis occurs when a short arterial vessel links two large arteries transversely; examples are found in the anastomosis between the two anterior cerebral arteries, that between the posterior tibial artery and the peroneal artery, and that between radial and ulnar arteries at the wrist.

RELATIONS OF BLOOD VESSELS

Arteries are usually more deeply situated than veins, although there are several superficial or subcutaneous arteries, such as the occipital, temporal and frontal arteries and the epigastric artery.

In the proximity of the joints of limbs arteries are located on the flexor surface, but, characteristically, there are many transverse vessels which provide a collateral circulation over the lateral parts of the joint.

Arteries are usually separated from bones by muscles and fasciae. When they are in contact with bone tissue they leave an imprint or vascular groove, for example the subclavian artery on the first rib.

Large arteries (thoracic aorta, subclavian, axillary, femoral and popliteal) lie close to a single vein which drains the same territory supplied by the artery. The other arteries are usually accompanied by two veins, satellite veins (*venae comitantes*), lying on either side of the artery. Such venae comitantes flank an artery, with numerous cross-connections, the whole assembly being enclosed in a single connective tissue sheath. The artery and the two satellite veins are often associated with a nerve; when they are surrounded by a common connective tissue sheath they form a vasculo-nervous fascicle.

The close association between the larger arteries and veins in the limbs allows the counterflow exchange of heat to take place: this mechanism promotes heat transfer from arterial to venous blood, and thus helps to preserve body heat. Counterflow heat exchange apparatuses are found in other organs, for example in the testis, where the pampiniform plexus of veins surrounds the testicular artery: with this arrangement, not only is body heat conserved, but also the temperature of the testis is kept below average body temperature (Evans 1949; Grant & Wright 1971; see also p. 1854). Counterflow exchange mechanisms involving ions are found in the microcirculation, as exemplified by the arterial and venous sinusoids which exist in the vasa recta of the renal medulla where countercurrent exchange retains sodium ions at a high concentration in the medulla (p. 1824), efferent venous blood transferring sodium ions to the afferent arterial supply.

CLASSIFICATION OF VESSELS

Arteries and veins are identified and classified according to their anatomical position. A large part of this section (p. 1824) deals with the distribution, position and other systematic aspects of individual blood vessels. Furthermore, vessels can be classified anatomically according to their size and wall structure (**10.2**). Arteries can be divided into elastic and muscular: although muscle cells and elastic tissue are present in all arteries, while the relative amount of elastic material is largest in the largest vessels, the relative amount of musculature increases progressively towards the smallest arteries. Classifications of arteries are often presented or referred to; these classifications, however, are vague at best, because the changes of the structural and functional parameters are usually continuous rather than discrete. The gradual change of most parameters does not favour any firm classification, if one was needed. There is also considerable variability in vessel properties between individuals, based on heredity, individual history and age.

Functionally, arteries are often subdivided into conducting, distributing and resistance vessels. (In simplified functional terms some authors distinguish only three classes of vessels: *resistance vessels*, or arteries, *exchange vessels*, or microcirculation vessels, and *capacitance vessels*, or veins.)

Conducting vessels. The large arteries arising from the heart and their main branches, these are characterized by the predominantly elastic properties of the wall.

Distributing vessels. These are smaller arteries reaching the individual organs and branching into them, and their wall is characterized by a conspicuous muscular component.

Resistance vessels. Mainly arterioles; because of their small size and abundant musculature, these are the main source of the peripheral resistance to blood flow, and they cause a marked drop in the pressure of blood.

Exchange vessels. This is the collective term for capillaries, sinusoids and postcapillary venules. Their wall allows or favours exchange between blood and the tissue fluid surrounding the cells, the essential function of circulatory systems. The exchange includes oxygen, carbon dioxide, nutrients, water and inorganic ions, vitamins, hormones, metabolic products, antibodies and defensive cells of various kinds. Arterioles, capillaries and venules constitute the *microvascular bed*, the site of the *microcirculation*.

Capacitance or reservoir vessels. Larger venules and veins form a coextensive but variable, large-volume, low-pressure array of these vessels conveying blood back to the heart. The high capacitance of these vessels is due to the distensibility (compliance) of their wall, so that the content of blood is large even at low transmural pressures. 14

Nerve of blood vessel

Vasa vasorum

Adventitia

External elastic lamina

Tunica media

Internal elastic lamina

Tunica intima

Endothelium of t. intima

Lumen

Lymphatic vessel

Variable basal lamina of endothelium

Collagen and elastin fibres in adventitia

Media and intima with elastic lamellae

Elastic artery

Smooth muscle cells in media

Muscular artery

Arteriole   *Venule*

Smooth muscle cells in media

Vein

10.2 Schematic drawing showing the principal structural features of the larger blood vessels. On the left the major layers and associated features of a muscular artery are depicted. On the right the particular features of an elastic artery, a muscular artery, an arteriole, a venule and a vein are shown, as they appear in transverse sections of these vessels.
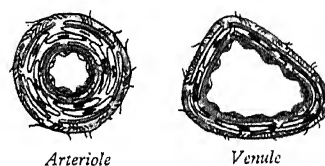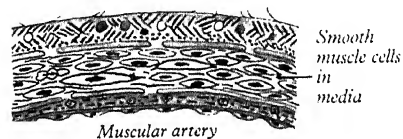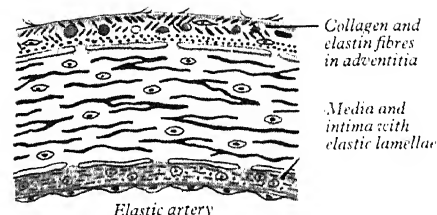
Because of the large relative volume of veins, this part of the vascular bed contains the largest amount of blood.

BLOOD CIRCULATION

The cardiovascular or circulatory system provides a continuous circulation of the blood, in a system which is virtually closed. The heart itself is a large, muscular, valved vessel, and has four chambers: right atrium, left atrium, right ventricle and left ventricle. (These somewhat misleading names are discussed on p. 1474.) Each atrium leads into a corresponding ventricle, the right and left chambers being separated by septa. The right and left sides of the heart are thus twin pumps, topographically combined in a single organ but interposed in series in the vascular system, which through their connections they separate into a systemic and a pulmonary circulation (constituting the so-called double circulation typical of birds and mammals, see p. 1472). The course of blood from left ventricle through the body at large to the right atrium forms the systemic circulation, its passage from the right ventricle via the lungs to the left atrium being the pulmonary circulation. The relatively short pulmonary system offers much less peripheral resistance than the systemic circulation, as is reflected in the lower pressures in the pulmonary distribution vessels and in the thinner walls of the right ventricle (p. 1480). The average output volume of blood from the right and left sides of the heart must, of course, be the same. The superior and inferior venae cavae return to the right atrium blood which has become deoxygenated, has taken up carbon dioxide and been otherwise modified during circulation through the tissues of the body. This blood then enters the right ventricle, which expels it via the pulmonary trunk to the lungs. In the pulmonary capillaries blood is brought into close proximity to the inspired air, releasing some carbon dioxide and acquiring oxygen. This oxygenated blood, returned by the pulmonary veins to the left atrium, enters the left ventricle, which pumps it into the aorta for general distribution.

Blood traversing the spleen, pancreas, stomach and intestines is not carried back directly to the heart but passes through the portal vein to the liver. This vein divides like an artery, ending in the hepatic sinusoids intimately associated with the laminae of hepatocytes; the sinusoids are drained by the hepatic veins to the inferior vena cava, whence blood is conveyed to the right atrium. This route is the *portal circulation*; its essential feature is that the blood supplied to abdominal viscera, such as the spleen, pancreas, stomach and intestine traverses not one but two sets of capillaries before returning to the heart. One set of capillaries originates from the coeliac and mesenteric vascular bed and provides oxygenated blood to the above-mentioned organs. These are drained into the portal vein, which gives rise to the second set of capillaries, the hepatic sinusoids. The sinusoids carry through the liver unoxygenated blood rich in absorption products from the intestine. The conspicuous musculature of the hepatic portal vein helps to propel the blood through the second microvascular bed. Passage through these two sets of capillaries enables the blood to transfer the products of digestion directly from the alimentary canal to the cells of the liver. Another venous portal circulation connects the median eminence and infundibulum of the hypothalamus with the pars distalis of the adenohypophysis (p. 1884) (Akmayev 1971). A venous portal system is present in the kidney of non-mammalian vertebrates. In essence, a venous portal system is a capillary network that lies between two veins, instead of between an artery and a vein, as in standard circulation. In other situations a capillary network is interposed between two arteries, notably in the renal glomeruli (see p. 1826).

Another circulation in the body is provided by the system of lymphatic vessels and lymph nodes, which conduct the lymph from the interstitial spaces between cells to the large veins of the thorax. Other, more restricted, circulations are those of the cerebrospinal fluid (CSF), perilymph, various endocochlear fluids, ocular aqueous humour, synovial fluid and the fluids of the coelomic spaces, namely the pericardial, pleural and peritoneal cavities.

Dynamic aspects of circulation

Propulsive force is generated not only by the heart, but also by the musculature of arteries and veins, and by the compression of vessels, especially veins, exerted by contracting skeletal muscles and by taut fasciae and ligaments. Other factors influencing the mechanical behaviour of the system are the elasticity of arteries, the viscosity of blood, and the friction between blood and the surface of vessels. The last factor is the origin of laminar flow (or its disruption, as in turbulent flow).

There is a marked influence of gravity on the cardiovascular system, expressed as *hydrostatic pressure*, which, of course, is influenced by the position of the body, whether upright or lying down for example. (In contrast, gravity has very limited effect on the physiology of viscera.) The *hydraulic pressure* is that generated to overcome the resistance offered by the arteries and by the viscosity of blood.

Blood pressure and blood-flow velocity are not steady or constant but pulsatile. Approximately one-quarter of the blood resides in the lesser circulation and the rest in the greater circulation. Three-quarters of the total volume of blood is in veins, especially in small veins of less than 1 mm diameter.

The total cross-section of the vascular network varies with the distance from the heart. It is minimal in the aorta, and it is maximal (and about 4000 × larger) at the level of the venules. The blood pressure, generated to a greater extent by the cardiac musculature and to a lesser extent by vascular musculature, falls progressively but not linearly along the arterial tree. Major falls of pressure occur immediately beyond the arterioles, where the smooth musculature ends, and at the entry into the venules, because of the sudden expansion of the vessel size.

Tissue tethering: an isolated vein can fully collapse and expel the blood it contains, whereas a vessel in situ, especially a vein, a microvessel or a lymphatic, may never collapse completely even when compressed in vivo because of the restraints imposed by tissue tethering.

METHODS OF STUDY OF VESSEL STRUCTURE

The course of large and medium-sized blood vessels can be studied by dissection; injection of coloured tracers may help to identify the vessels. (It is salutary to remember how many centuries it took to work out the essence of the vascular system, even when the necessary means of observation were fully available.) Measurements of vessel size cannot normally be carried out on the cadaver. They can be carried out in vivo or in vessels fixed in situ by lumenal perfusion of the fixative at physiological pressure.

Vascular casts are prepared by injecting under pressure a fluid, coloured resin into the vascular bed of an organ, letting the resin polymerize and digesting away with acid all the tissue. The cast reproduces all the vascular spaces in the injected organ, and, in the case of the microcirculation, can be studied in a scanning electron microscope. The lumenal surface of the endothelium can be studied by scanning electron microscopy after covering it with an ultra-thin layer of metal (10.7A, 8A), while freeze-fracture preparations reveal the internal structure of the cell membrane (10.7B). To view intrinsic features of the vessel wall by scanning microscopy requires micro-dissection and chemical digestion of collagen and elastic materials, for example with collagenase or strong alkali (10.8B).

Histological sections are the method of choice to study the structure of vessel walls: transverse sections are orthogonal to the vessel's long axis, longitudinal sections are parallel to this axis and ideally should pass through the middle of the vessel. Since great structural distortion is produced by the collapse of the vessel, fixation under controlled conditions of distension or pressure is paramount for structural analysis.

HISTOLOGY OF THE VESSEL WALL

In cross-section a blood vessel has a circular profile and, with few exceptions, a wall of uniform thickness. Small but appreciable differences in wall thickness are found in very curved vessels such as the aorta arch: on the inner curve, where the wall stress is greater,

the wall is thicker than on the outer curve. The diameter of the vessel and thickness of the wall are greatly affected by contraction of the wall; great caution must be exerted in evaluating these parameters in histological sections, especially in postmortem material. On the other hand, these two structural parameters are essential to establish the mechanical properties of any vessel. For the structural analysis of blood vessels, irrespective of size, and with the exception of capillaries and venules, three concentric parts or layers (or tunicae) are recognized in the vessel wall (10.2):

- the intima (strictly speaking the tunica intima), or innermost layer, whose main component, the endothelium, lines the entire vascular tree.
- the media (tunica media), made of muscle tissue, elastic fibres and collagen; while it is by far the thickest layer in arteries, the media is absent in capillaries and is comparatively thin in veins.
- the adventitia (tunica adventitia), the outer wrapping of the vessel, made of connective tissue nerves and capillaries. The adventitia links the vessels to the surrounding tissues.

The main histological components of the vessel wall are therefore an endothelium, elastic tissue, muscle tissue, collagen and connective tissue (10.3). With the exception of the endothelium, the general features of the various tissues have already been described in sections 2 and 9.
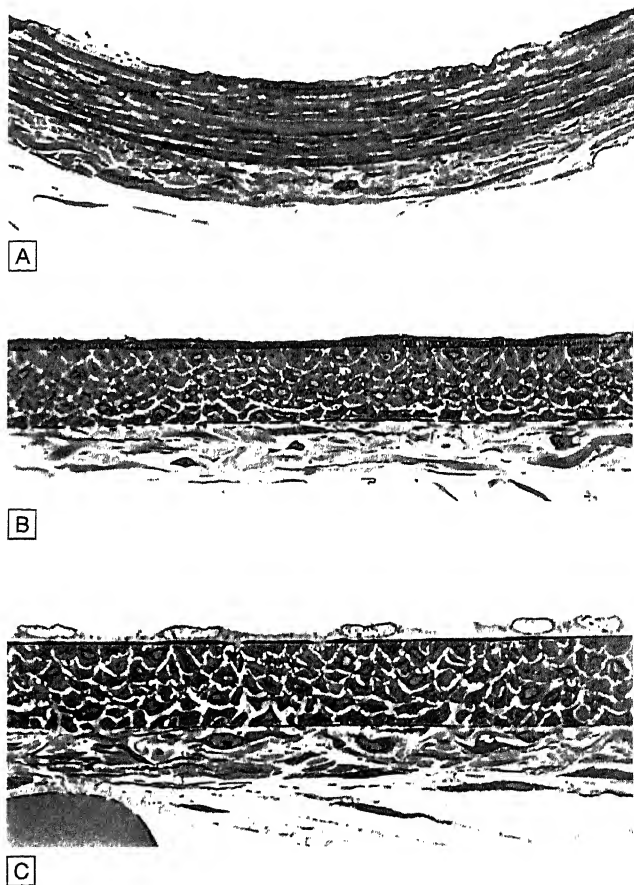
10.3 Histological sections of a muscular artery, fixed in situ in a condition of physiological distension. A. The artery is sectioned transversely, and the muscle cells of the media are cut longitudinally. Magnification × 510. B. The artery is sectioned longitudinally, and the muscle cells are cut transversely. Magnification × 510. C. At higher magnification, the endothelial cells can be seen, somewhat elongated in the direction of the blood flow; the dark line beneath the endothelium is the inner elastic lamina, which shows fenestration, and is straight in this preparation because it was fixed while distended. The tunica media is made of five or six arrays of muscle cells, which are transversely sectioned. The tunica adventitia displays collagen fibres and fibroblasts. Magnification × 510.

ENDOTHELIUM

The endothelium is a monolayer of flattened polygonal cells which extend continuously over the luminal surface of the entire vascular tree (10.4, 5, 6, 11). Its structure includes specific features in different regions of the vascular bed. The endothelium is a key component of the vessel wall because it serves several major physiological roles, as listed below.

- Because of their position, endothelial cells influence blood flow.
- They regulate the diffusion of substances and of cells, out of and into the circulating blood, across cell junctions and through their cytoplasm.
- They participate in the process of coagulation (see p. 1400), by secreting clotting factors, and in the process of fibrinolysis.
- They have selective phagocytic activity and extract substances from the blood, and have other metabolic activities; for example, the endothelium of the pulmonary vessels removes and inactivates several polypeptides, biogenic amines, bradykinin, prostaglandins and lipids from the circulating blood. Endothelium Derived Relaxing Factor (Ryan & Ryan 1984).
- Endothelial cells secrete substances (endothelium derived relaxing factor or nitric oxide, and endothelins) which affect vasomotility, and probably also substances which promote the growth of the endothelium itself, such as Basic Fibroblastic Growth Factor (b-FGF) (Schweigerer et al 1987).
- They are sensitive to the transmural stretch imposed by the pulse, via stretch-sensitive ionic channels in the cell membrane, thus endowing the vessel wall with a sensor or a sensory element.
- They can synthesize (and at least they do so in in vitro cultures) fibronectin, laminin, collagen, elastin and other components of the subendothelium (Ryan & Ryan 1984).
- They are capable of proliferating to provide new cells during the period of increasing size of a blood vessel, to replace damaged or exfoliated endothelial cells, and also to provide growing solid cords of cells which are the forerunners of new blood vessels (see angiogenesis, p. 1470).

Endothelial cells are wide and thin, tile-like and slightly curved to fit the curvature of the vessel. They are somewhat elongated in the direction of blood flow, especially in arteries (10.11). Endothelial cells firmly adhere to each other at their edges, so that the lining of t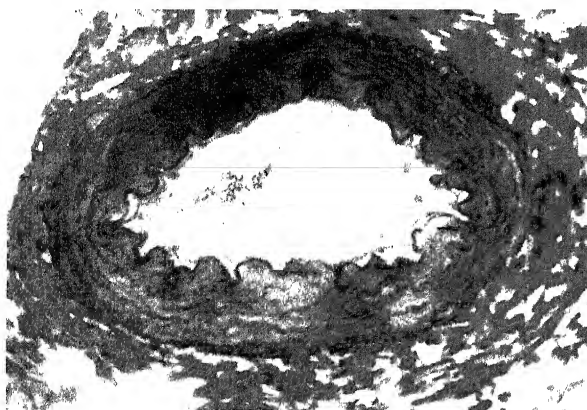he lumen presents no discontinuity (except in sinusoids, see p. 1466; 10.4.) The thickness of endothelial cells is maximal at the level of their nucleus, where it can reach 2–3 μm, this part of the cell often bulging slightly into the lumen (10.3c). Elsewhere, the endothelial cell is thinner and laminar; in capillaries, these portions of the cell are very attenuated, often measuring as little as 0.2 μm in thickness (10.12).

The *luminal surface* of the endothelium is relatively smooth. However, it is common to find endothelial laminar projections into the lumen, especially near the cell junctions. The cell surface is pitted by the numerous caveolae (10.7B) and the membrane is coated by a prominent glycocalyx (Luft 1966; Ryan & Ryan 1984). The glycocalyx is a highly-charged, polysaccharide-rich felt of glycoprotei

10.4A Part of a transverse section of the aorta of a monkey, stained with haematoxylin and eosin, showing the distribution of cell nuclei. Magnification ×100.

10.4B Part of a transverse section of a young human aorta stained with Verhoeff's stain for elastin. Note the density of the concentric fenestrated elastic lamellae. Magnification ×100.

10.4C Transverse section of a small muscular artery, stained with Verhoeff's stain for elastin and van Gieson stain for collagen. Note the prominent inner elastic lamina, which is heavily folded because the vessel was fixed postmortem when collapsed and virtually empty. Magnification ×200.

10.5 Transverse section of two small muscular arteries and a small vein, stained with haematoxylin and eosin. Numerous venules and capillaries are included but are indistinct at this magnification. (Supplied by D R Turner of the Department of Pathology, Guy's Hospital Medical School.)
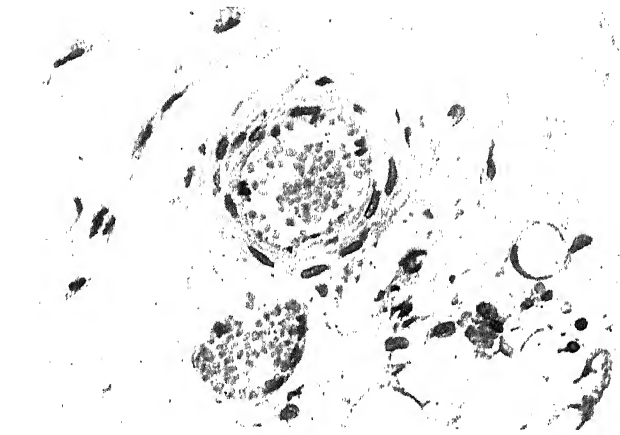
10.6 Transverse section of a large arteriole and venule in loose connective tissue, stained with haematoxylin and eosin. (Source as 10.5.)

anchored to the cell membrane, which controls the transport of solutes and may mediate the mechanical effects of blood flow on the endothelial cells. Because of the high charge density the glycocalyx may contribute to the non-thrombogenic properties of the surface of the intact endothelium. The glycocalyx is not seen in standard electron micrographs of the endothelium, but can be visualized with electron-dense substances, such as ruthenium red, which bind specifically to glycoproteins. The abluminal surface is also pitted by caveolae and it rests over a basal lamina.

Caveolae are consistently observed in all endothelial cells. These invaginations of the cell membrane measure about 200 × 50 nm; their membrane is in continuity with the cell membrane proper and their cavity opens into the extracellular space through a narrow neck (10.7B, 12B). Their spatial density is of the order of several tens per square micron of cell surface; because of their large number, more than half of the plasma membrane at the cell surface is in the form of caveolae. Caveolae are regarded by several authors as manifestations of a process of transcytosis: the membrane is pinched in from **one surface** of the endothelial cell, and forms a caveola (which includes a tiny amount of extracellular fluid) that eventually detaches itself and becomes a free-moving spherical vesicle in the cytoplasm; the vesicle then merges with the membrane on the **other**

surface of the cell, again forming a caveola (and again releasing its tiny amount of fluid into the extracellular space). In this interpretation, a 'shuttle' system, caveola–vesicle–caveola, transports material across the endothelial cell, in both directions. It is a 'bulk' transport because it is relatively non-selective and it involves a sizeable amount of extracellular fluid. There have been strong doubts about this form of transendothelial transport, mainly because of its lack of selectivity. Studies of serial sections of endothelial cells of capillaries have shown that even those structures which appear as free-floating vesicles in a single section are actually connected with the extracellular space; true vesicles seem to be exceedingly rare and the caveolae are constantly open to the extracellular space (Frokjaer-Jensen 1984). In other cell types, such as smooth muscle cells, caveolae are known to be stable structures, not involved in endocytosis (unlike coated pits and coated vesicles).

Cytoplasmic organelles of endothelial cells include mitochondria, granular and agranular endoplasmic reticulum, some free ribosomes and occasionally a pair of centrioles. In spite of the evidence of chemical factors being released by endothelial cells, cytological signs of secretion are not prominent. Bundles of microfilaments and intermediate filaments are also found. The former are made of actin and the latter are usually vimentin filaments. Filaments contribute to maintaining a certain shape of the cell and impart mechanical stability, and presumably they play an important role when the cell changes shape or migrates. Characteristic organelles of endothelial cells are the *Weibel-Palade bodies*, which are cytoplasmic vesicles, elongated, 0.2 × 2–3 μm, containing regularly spaced tubular structures parallel to the long axis which give rise to a striation. These organelles produce and store a large glycoprotein known as von Willebrand protein (or factor VIII), which mediates the binding of platelets to the extracellular matrix of the subendothelium after vascular injury. Von Willebrand protein is also produced, in larger amounts, by megakaryocytes and is stored in platelets.

Seen from the lumen, endothelial cells usually have a polygonal contour. At their edge they adhere to adjacent cells through an area of apposition where junctions of the adherens, communicans and occludens types are found (the so-called junctional complex). The area of apposition can be a straight line covering the shortest distance between luminal and abluminal aspects of the endothelium. More commonly, there is an oblique or a tortuous line of apposition, sometimes with overlap or interdigitation between endothelial cells. Often a laminar process from the edge of an endothelial cell projects into the lumen and seems to guard the area of apposition of the endothelial cells. The role of these projections, however, is unknown. A tight junction forms a belt (zonula occludens) around the contour
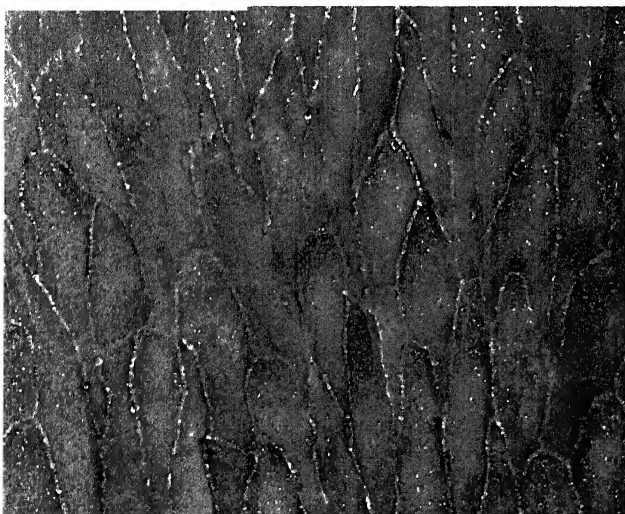
10.7A Inner surface of the endothelium of a basilar artery, examined by scanning electron microscopy. The lumenal surface is tessellated by endothelial cells which are tightly packed and elongated in the direction of the blood flow. Magnification × 1250. (Supplied by Masoud Alian of University College London.)
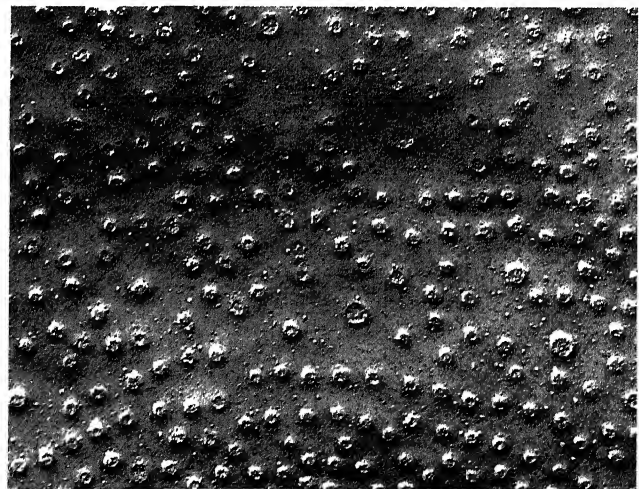
10.7B Freeze-fracture preparation of the plasma membrane of an endothelial cell. The E-face of the membrane shows innumerable caveolae fractured at the level of their neck. Magnification × 40 000.

of an endothelial cell, involving all the cells that are directly adjacent. These tight junctions are best visualized by freeze-fracture, and they vary in extent in different vascular regions. They provide a seal which blocks or restricts movement of fluids through the intercellular gaps of the endothelium; they also limit the lateral diffusion of membrane proteins and lipid between the luminal and the abluminal domains of the cell membrane. Gap junctions and, occasionally, intermediate junctions accompany the tight junctions between endothelial cells (Hüttner et al 1973); they invariably reside further away from the lumen than the tight junctions. The gap junctions are likely to allow the bi-directional and non-selective diffusion of ions and small molecules between endothelial cells. Cell contacts between endothelial cells and muscle cells are common in arterioles, where the separation between endothelium and media is reduced and the inner elastic lamina is very thin or absent.

Endothelial cells can synthesize and secrete collagen; thus they are regarded as contributing to the formation of the inner elastic lamina.

SMOOTH MUSCLE

This is invariably of the smooth type (see p. 738), with the exception of small segments of the pulmonary veins (p. 738) which, in the portion nearest to the heart, have striated musculature of the cardiac type. Smooth muscle cells are the only cell type found in the media of most arteries of mammals (10.7A, 11). One function of smooth muscle in blood vessels is to reduce, with their contraction, the vessel's lumen and hence the flow through it, an action which has the effect of raising the pressure on the proximal side. This role is particularly effective in small resistance vessels where the thickness of the wall is great relative to the diameter of the vessel. Another function of smooth muscle is to alter the stiffness of the wall, causing no constriction (isometric contraction) but affecting the distensibility of the wall and the propagation of pulse. The mechanics of the musculature of the media is complex for several reasons: because the structures involved have a concentric arrangement; because the tissue is incompressible and therefore of constant volume; because the spatial arrangement of muscle cells and fibrous extracellular materials is variable and not well understood; because materials of different mechanical properties and different spatial arrangement are tightly linked together. Properties of distensibility, strength, self-support, elasticity, rigidity, concentric constriction, are interrelated and finely balanced in the various regions of the vascular bed.

Muscle cells are responsible for the active motility of the vessel wall. These cells also synthesize and secrete elastin, collagen, muco-polysaccharides and other extracellular components which bear directly on the mechanical properties of the vessel. The muscle cells of the arterial media have been rightly labelled multifunctional mesenchymal cells (Wissler 1968). After damage to the endothelium, muscle cells migrate into the intima and proliferate, forming bundles of longitudinally oriented muscle cells (neo-intima: Fishman et al 1975). In pathological conditions, muscle cells with their fatty degeneration participate in the formation of atheromatous plaques.

The vascular musculature is made of single, uninucleated muscle cells (vascular muscle cells) which have many common structural features with visceral muscle cells, but are also somewhat different (10.4A, 8, 11). The basic structural features of smooth muscles are described elsewhere (p. 771). In large arteries, where the blood pressure is high and the stress of the wall is high, the muscle cells are shorter (60–200 μm) and smaller in volume than in visceral muscles. The cell profile is very irregular and the cell membrane has many conspicuous dense bands where the contractile apparatus and the extracellular fibrous components are linked to each other. In arterioles and veins, smooth muscle cells resemble more closely visceral muscle cells.

The cells are packed with myofilaments and with elements of the cytoskeleton, including intermediate filaments. The latter, which are invariably of the desmin type in visceral smooth muscles, are made of vimentin or of vimentin and desmin in vascular muscle cells.

Cell-to-cell junctions are mainly of the adherens type and provide mechanical coupling between the cells (10.11). There is also a small number of gap junctions. Far more numerous than cell-to-cell junctions, especially in arteries, are the junctions between muscle cell and connective tissue matrix (cell-to-stroma junctions). Between adjacent muscle cells there are also interdigitations and extensive areas of apposition without apparent membrane specializations; they involve fusion or disappearance of the basal laminae and are likely to provide some adhesion between the two cells.

The orientation of muscle cells within the media has been the object of several investigations, and there is no conclusive account of this anatomical feature. In most arteries the orientation of the cells is approximately circumferential; over a wide range of vessel sizes the deviation from circumferential is minimal (Canham & Mullin 1978; Walmsley 1983), except for the occasional presence of a bundle of musculature of unexpected orientation within the media. In large vessels the musculature is divided into layers or into bundles and there are some variations even between adjacent lamellae. The circumferential arrangement appears more irregular when the vessel contracts and may be grossly disrupted in collapsed arteries. A helical orientation (as in a cylindrical spring) of muscle cells has
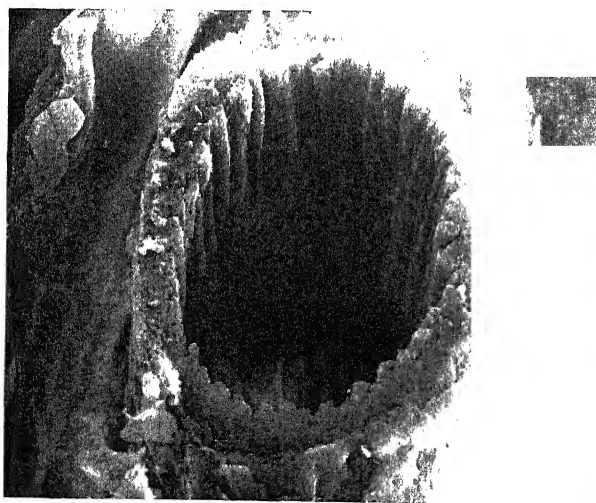
10.8A A small vessel approaching the surface of the brain, examined by scanning electron microscopy. The free surface of the endothelium is corrugated by the relief of the endothelial cells. Magnification × 750. (Source as **10.7A.**)
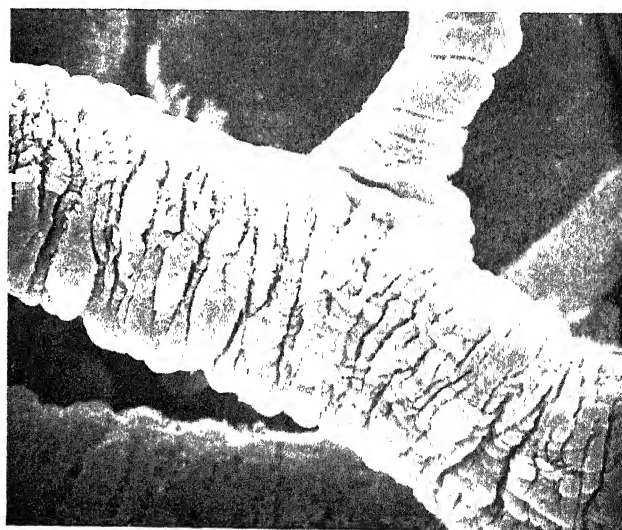
10.8B Arteriole isolated from the mesentery, freed of its adventitia by enzymatic digestion and examined by scanning electron microscopy. The muscle cells are contracted and are wound circumferentially in the vessel wall. Magnification × 1000. (Micrograph supplied by Professor Komuro, School of Human Sciences, Waseda University, Japan.)

been described in the lamellae of some large arteries. In the rat aorta, for example, where right- and left-handed helices may be present in successive lamellae (Rhodin 1962) has reported that the pitch increases during postnatal growth. In large elastic arteries, muscle cells often connect the elastic lamellae on either side, hence they have also a slightly spiral orientation (as in a two-dimensional spring, such as a watch spring). The spatial orientation of medial muscle cells is regarded as one of the anatomical factors affecting the mechanical properties of the vessel wall. It is possible, however, that the exact orientation of the muscle cells is not the most significant factor in this respect. Because of the cohesion of the media, the dense packing of cells and stroma, the vast number of cell-to-cell junctions and cell-to-stroma junctions and the lateral dislocation of volume when the cell shortens, a highly geometrical arrangement of the contracting cells is not a major requirement for an adequate functional performance.

In physiological conditions the intima of some large arteries contains a few smooth muscle cells, longitudinally arranged. In large arterioles some bundles of longitudinally oriented musculature are found near the adventitia. While in small arteries and arterioles the arrangement of the musculature becomes more regular and invariably circumferential (10.8B, 11), in veins the arrangement of the musculature is more variable (see p. 1466).

Even when they run circumferentially, muscle cells in the media of large arteries are only slightly curved, and many cell lengths are needed to make up the circumference of the vessel. In contrast, in arterioles the muscle cells are tightly coiled (see p. 1463).

COLLAGEN AND ELASTIC MATERIAL

A major constituent of the vessel wall are the extracellular materials, collectively known as the *stroma* or *matrix*. In large arteries and veins this constitutes more than half of the mass of the wall, and is mainly made of collagen and elastin (10.11). Other fibrous components, such as fibronectin microfibrils, and abundant amorphous or soluble materials are present in the extracellular spaces of the vessel wall.

Elastic material is found in all arteries and veins and it is especially abundant in elastic arteries (10.11A). Individual *elastic fibres* (0.1–1.0 μm in diameter) anastomose with each other forming net-like structures, which spread predominantly in a circumferential direction (10.8B). A more extensive degree of fusion produces lamellae of elastic material, which are usually perforated but separate layers of muscle cells, thus allowing the formation of lamellar 'units' (see p. 1463). A conspicuous elastic lamella occurs in arteries, between intima and media, the *inner elastic lamina*. This lamella is a tube of elastic material which allows the vessel to recoil after distension. When the intraluminar pressure falls below physiological limits, the inner elastic lamina is compressed sideways and it coils up into a regular corrugated shape (10.4C): in these conditions the lumen is much reduced but is not obliterated, and the profile of the artery remains circular. Fenestrations in the elastic lamina allow materials to diffuse between intima and media. An *outer elastic lamina*, similar in appearance but markedly less well developed than the inner elastic lamina, is situated at the outer aspect of the media at the boundary with the adventitia. Elastic fibres are less abundant in the adventitia.

Collagen fibrils (transversely banded cables of 30–50 nm diameter, see p. 81) are found in all three tunicae (10.11), and especially around the muscle cells of the media. Collagen is abundant in the adventitia where it forms large bundles of fibrils (*collagen fibres*) which increase in size from its innermost component near the media to its outermost component.

In general terms, collagen and elastic fibres in the media run parallel or at a small angle to those of the muscle cells, and therefore they are mainly circumferentially arranged. In contrast, the predominant arrangement of collagen fibres in the adventitia is longitudinal, and this imposes constraints on the elongation of large vessels under pressure. In large arteries, for example, the radial distension under the effect of the pulse far exceeds the longitudinal distension (Burton 1954). While the outer 'sheath' of collagen, i.e. that of the adventitia, limits the distensibility of the vessel, the collagen network of the media mainly provides attachment to the muscle cells and transmits force around the circumference of the vessel. While collagen fibres are inextensible, elastic fibres are very highly extensible. They provide ample attachment to the muscle cells, favouring a uniform spread of the muscle tension around the vessel wall; in a distended vessel, the elastic fibres store energy and, by recoiling, help to restore the resting length and calibre.

The extracellular material of the tunica media, including collagen and elastic fibres, is produced by the muscle cells during development. Its turnover is slow compared to that in other tissues, and this too is controlled by the muscle cells of the media. In the adventitia, collagen is synthesized and secreted by fibroblasts, as in other connective tissues. During development in postnatal life, while vessels increase in diameter and wall thickness, there is an increase in elastin and collagen content. Subsequent changes in vessel structure include an increase in the collagen-to-elastin ratio, with a reduction in vessel elasticity.

PERICYTES

In capillaries, where a proper adventitia is absent and where there are no muscle cells, other cells, the pericytes, are present at the outer surface of the vessel (10.12A). Pericytes, or cells of Rouget, are known under various other names and probably do not represent a uniform population of cells. They are elongated, have a bulging cell body and long laminar processes spread around the capillary endothelium. They do not form a continuous layer but their shape suggests a tight grip of the capillary and a mechanical supporting role. They (or some of them) may have a phagocytic role. It is possible that some pericytes are a source of new endothelial cells, to replace any which may become damaged in the endothelium, or of mesenchymal cells or of muscle cells. Their number and morphology are very variable. Because they contain some bundles of filaments, and they contain, as shown by immunohistochemistry, actin, myosin, tropomyosin and desmin (Uehara et al 1990), the pericytes are regarded by some authors as contractile cells (Rhodin 1962): the suggestion that they are a primitive type of muscle cell (Zimmermann 1923) is, however, purely speculative. Most pericytes have areas of close apposition with endothelial cells, occasionally forming adherens junctions (Forbes et al 1977). These are the only areas where a basal lamina does not coat the surface of the pericyte.

INTRODUCTION

A remarkable feature of the immune system is the integration of functionally different organs and tissues by constant migration of lymphoid cells from one site to another along blood and lymphatic vessels. The migration of lymphocytes and the interactions of activated cells during immune responses are regulated by cell-surface molecules. Adhesive interactions between cells, and between cells and the extracellular matrix, are vital to all developmental processes and have a crucial role in a well-functioning immune system throughout life (Springer 1990).

Mature 'virgin' lymphocytes from the bone marrow and thymus, the sites of primary lymphoid organs, enter the blood circulation and reach secondary lymphoid organs such as lymph nodes, spleen, tonsils, Peyer's patches and appendix, as well as dispersed lymphoid tissues. The latter can be associated with skin ('skin associated lymphoid tissue' or SALT), or the mucosal surfaces of the gastro-intestinal tract ('gut associated lymphoid tissue' or GALT), the respiratory tract

('bronchus associated lymphoid tissue' or BALT) and the urogenital tract (a part of the 'mucosa associated lymphoid tissue' or MALT). The secondary lymphoid organs and tissues guard the portals of entry for antigens and provide a favourable environment for the interactions of antigens with lymphocytes (Brandtzaeg 1984). Finally, using the efferent lymphatic drainage, both virgin and memory lymphocytes re-enter the venous limb of blood circulation via the lymphatic trunks and the thoracic duct and recirculate. This arrangement maximizes the probability of effective antigen–lymphocyte interaction throughout the body.

VASCULAR ENDOTHELIUM

The lumen of all blood vessels is lined by endothelial cells which maintain the fluidity of the blood, regulate the interactions of circulating cells and platelets with the vessel walls and form the interface between the bloodstream and extravascular tissues. Although the endothelium consists of a monolayer of cells it has, under normal conditions, two different surfaces that exhibit morphological as well as biochemical polarity: the luminal, non-thrombogenic surface, and the abluminal, adhesive surface (de Groot 1987). The abluminal surface faces the deeper layers of the vessel wall and is adhesive for platelets. In contrast, the luminal surface of endothelial cells can be considered blood cell-like, a haemocompatible interface. It represents a natural barrier capable of regulating the circulating levels of several vasoactive and platelet-active mediators and it does not support the adherence of leucocytes or platelets (Brown 1994). However, perturbation of endothelial cells induces the production of platelet-activation factor (PAF), which is a potent stimulus for platelet aggregation.

Many functions of human vascular endothelial cells are dynamic rather than fixed. For example, on endothelial injury, with the exposing of the subendothelial matrix, the nearby uninjured endothelial cells migrate across the denuded surface and can re-endothelialize a small defect within hours (Jarrell et al 1987).

LYMPHOCYTE CIRCULATION AND MIGRATION INTO LYMPHOID AND NON-LYMPHOID ORGANS

Under normal conditions there is a continuous flow of lymphocyte through secondary lymphoid organs. These organs are structurally analogous in that they all possess: first, a complex framework which provides ideal conditions for interactions between lymphocytes and antigen-presenting cells; second, separate domains which are more or less specific for T or B

cells; and third, specialized segments of vasculature supporting the extravasation of circulating lymphocytes, known as the postcapillary or high endothelial venules (HEVs) (10.9A).

The bulk of the lymphocyte traffic is thought to pass through HEVs located in the parafollicular areas of lymph nodes, palatine and nasopharyngeal tonsils, Peyer's patches, appendix and the mucosal lymphoid tissue aggregates of MALT. There are no HEVs in the spleen, yet more lymphocytes migrate through this organ than through all lymph nodes (Pabst & Binns 1989). Although it has been proposed that the marginal sinus lining cells may be responsible for the initial arrest of blood lymphocytes in the splenic marginal zones, little is known about the mechanism of lymphocyte traffic through the spleen (Stevens & Lowe 1992; Picker & Butcher 1992).

The HEVs are also absent from primary lymphoid organs (bone marrow and thymus) and, normally, they are not present in non-lymphoid organs and tissues in spite of a continuous lymphocytic migration through them, in the course of general surveillance. Here, migration may occur through capillaries, sinusoids and possibly low endothelial venules. Pabst and Binns (1989) studied the migration route of lymphocyte subsets in pigs and sheep using suspensions of in vitro fluorescein isothiocyanate (FITC) labelled peripheral blood lymphocytes. Within the first few minutes 40% of lymphocytes were found in the lungs and 14–21% in the liver. Thus, similar to spleen, the lungs and the liver are not only sites for capturing effete cells but these non-lymphoid organs actively participate in recirculation of lymphocytes.

Interestingly, HEV-like vessels have been found at many sites of chronic inflammation where they are believed to support the extravasation of large numbers of leucocytes. Neutrophils, lymphocytes and monocytes migrate into inflamed tissue sites with class-specific kinetics: the relatively nonspecific neutrophils appear within minutes of stimulation while the antigen-specific T and B cells and monocytes arrive within hours but may remain for days (Osborn 1990). One of the best-documented examples of this phenomenon is the rheumatoid synovium (Freemont et al 1983; Koch et al 1991).

Some lymphocytes move from one secondary lymphoid organ to another via the blood and lymphatic vessels while others stay resident in these organs for a variable period of time. For example, antigen-specific lymphocytes are preferentially retained in those lymph nodes which drain the source of the antigen (Picker & Butcher 1992). Moreover, there is evidence for carefully regulated, non-random migration of lymphocytes to particular anatomical sites, referred to as 'homing' (Rosen

1989; Springer 1990; Picker & Butcher 1992). Thus, lymphocytes which home to the gut are thought to be transported selectively across gut specific microvasculature, while other populations of lymphocytes home in a similar manner to different target organs, such as the tonsils or peripheral lymph nodes. This tissue specificity for lymphocyte homing is thought to be relative rather than absolute and may be determined by a combination of multiple factors rather than by a single specific factor (Shimizu et al 1992).

It has been now generally accepted that circulating lymphocytes are leaving the HEVs to home into the lymphoid compartments of secondary lymphoid organs and tissues, although in the past some researchers held the opposite view. In 1929 Ehrich proposed that in a lymph node 'small lymphocytes were immigrating into the vein lined with endothelium consisting of very high and crowded cells'. The physiological significance and the direction of transendothelial migration of lymphocytes had not been appreciated until the original autoradiographic experiments of Gowans and Knight (1964).

HIGH ENDOTHELIAL VENULES

High endothelial venules are found in most mammalian species and recognized by the conspicuous plump endothelial lining associated with numerous luminal mural and extramural lymphocytes (10.9A). These vessels are located within the T cell domains, between and around lymphoid follicles in all secondary lymphoid organs and tissues, with the exception of the spleen. In the human palatine tonsil HEVs were also seen in the lower parts of reticulated crypt epithelium (Perry et al 1992). On account of their position and diameter of 7–30 μm, HEVs are also referred to as post-capillary venules. They begin at a junction of flat-walled venous capillary limbs, receive venules draining the surrounding lymphoid follicles and end as tributaries to larger veins (Ohtani et al 1989).

The luminal aspect of HEVs presents a so-called 'cobblestones' appearance covered with a prominent glycocalyx (Anderson & Anderson, 1975). The single layer of high endothelial cells (HECs) rests on endothelial basement membrane which is intimately related to pericytes. The pericytes, in turn, are surrounded by their basement membrane and a small amount of connective tissue (10.9B). The HECs are linked by discontinuous macular junctions at their apical and basal aspects, which may be circumnavigated by migrating lymphocytes (Anderson & Anderson 1976).

Ultrastructurally, HECs have the characteristics of metabolically active secretory cells. They contain large, rounded euchromatic nuclei with one or two nucleoli, prominent Golgi regions,
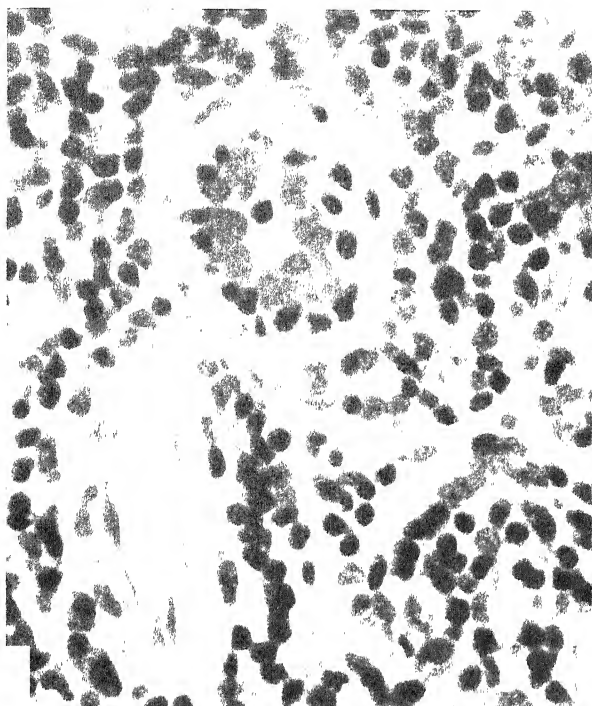
10.9A The height of the endothelium of transversely sectioned high endothelial venule (*HEV; upper field*), lined with columnar cells and associated with numerous dark blue stained lymphocytes, contrasts with the neighbouring low endothelial venule (*left lower field*) and lymphatic vessel (*right lower field*). Human palatine tonsil. Methylene blue/Azur II.
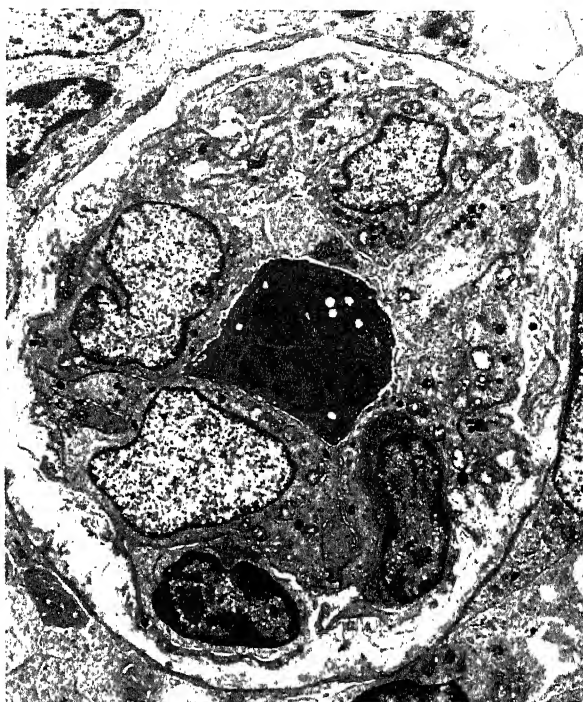
10.9B Transverse section of HEV in human palatine tonsil. The vessel lumen is occupied by a neutrophil completely surrounded by high endothelial cells. The electronlucent nuclei of three of these cells are present in the plane of this section. Pericyte (*right*) with its attenuated processes lies externally to the undulating endothelial basal lamina and a small amount of connective tissue. Note the position of the two mural (*right lower field*) and the extramural (*left upper field*) lymphocytes. TEM. Magnification × 3 000.
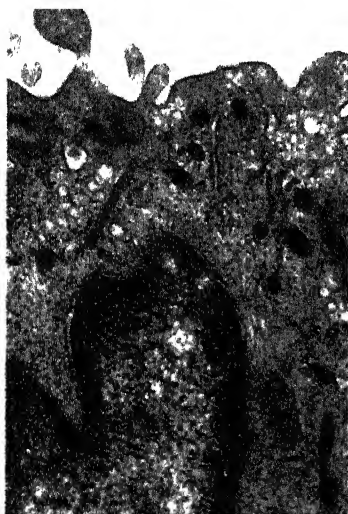
10.9c High endothelial cell in rheumatoid synovium containing many sectioned profiles of the microtubular Weibel-Palade bodies above and around the nucleus. TEM. Magnification × 20 000.

many mitochondria, ribosomes and pinocytotic vesicles. Typically, they also possess the microtubular Weibel-Palade bodies in which Factor VIII and P-selectin are stored (**10.9c**). Stimulation of the endothelium by thrombin, histamin or reactive oxygen species results in rapid translocation and redistribution of P-selectin to the endothelial surface (Hogg 1992; Cronstein & Weissmann 1993). The 10–12 μm high cuboidal or columnar cells protrude into the lumen and the rate of collision between circulating blood cells and vessel wall is increased. Subsequently collision attachment and migration of leucocytes can follow.

MOLECULAR BASIS OF HOMING LEUCOCYTES

Cell adhesion molecules (CAMs) is a collective term for cell surface glycoproteins regulating the adhesion between cells. Endothelial adhesion molecules facilitate the attachment of free circulating leucocytes to the vessel walls. A rapid transition between adherent and non-adherent states of leucocytes is essential for the maintenance of their dual function of

immune surveillance and responsiveness. However, fundamental changes occur on endothelium in the vicinity of an inflammatory response when inflammatory mediators such as lipopolysaccharide, interleukin-1 (IL-1), tumour necrosis factor alfa (TNF-*a*) or gamma interferon (*y*-IFN) increase the adhesion but reduce the selectivity of extravasating leucocytes (Shimizu et al 1992).

Many of the adhesion molecules that mediate interactions between blood leucocytes and HEVs or cytokine-activated endothelium have been identified. These molecules can be divided into three general categories: the selectin family, the integrin family and the immunoglobulin supergene family. The selectin and integrin molecules are expressed on leucocytes and mediate adhesion of circulating cells to the endothelium, whereas selectins and members of the immunoglobulin supergene family are expressed on the endothelium and provide the 'sticky' substrate to which leucocytes can adhere (Springer 1990; Cronstein & Weissmann 1993).

Selectins

Three molecules have been identified so

far as members of the selectin family of adhesive proteins. They are the L-selectin (also known as lymphocyte homing receptor, CD62L, Leu-8, Mel-14, LAM-1), E-selectin (CD62E, ELAM-1) and P-selectin (CD62P, GMP-140, PADGEM). Selectins have a characteristic amino-terminal lectin domain, an epidermal growth factor-like domain and a variable number of complement regulatory domains. The selectin molecules bind to specific sialyated carbohydrates, including sialyl Lewis X, which is a unique feature among adhesive proteins (Polley et al 1991).

The L-selectin is expressed on most leucocytes and its endothelial ligand has been termed recently GlyCAM-1 (Imai et al 1993). Importantly, L-selectin mediates homing of lymphocytes to peripheral lymph nodes as well as accumulation of neutrophils and monocytes at sites of inflammation.

The E-selectin is a molecule which is only transiently expressed on endothelium. It is an inducible adhesion molecule which was first described as mediating adhesion of neutrophils to inflammatory cytokine activated endothelium (Bevilacqua et al 1989).

The P-selectin is rapidly mobilized to the endothelial surface by fusion from storage in Weibel-Palade bodies following stimulation of the endothelium. Since P-selectin is quickly endocytosed by the endothelial cells its expression is only short lived. P-selectin binds to ligands expressed on neutrophils, platelets, and monocytes and, similar to E-selectin, it tethers leucocytes to endothelium at sites of inflammation (Zimmerman et al 1992).

Integrins

The integrins are a large family of molecules mediating cell-to-cell adhesion as well as interactions of cells with intercellular substances. They are therefore essential in regulating spatial orientation and cell movement. Integrins represent a group of related heterodimeric adhesion proteins and each molecule comprises an α- and a β-subunit (β1, β2 and β3).

The β1 integrins are a subfamily of six molecules known as 'very late antigens' (VLAs) which function mainly as receptors for components of extracellular matrix. The VLA-1 and VLA-2 adhesion molecules were found to be expressed on lymphocytes only 2 to 4 weeks after antigenic stimulation in vitro and they bind to the extracellular matrix (Keelan & Haskard 1992). On the other hand the VLA-4 integrin (α4β1, CD49d/CD29), which is present on resting lymphocytes, monocytes and eosinophils, binds also to its ligand on activated endothelium, the vascular cell adhesion molecule 1 (VCAM-1 CD106).

In contrast to β1 integrins the expression of β2 integrins is limited to white blood cells. Although the leucocyte integrins are
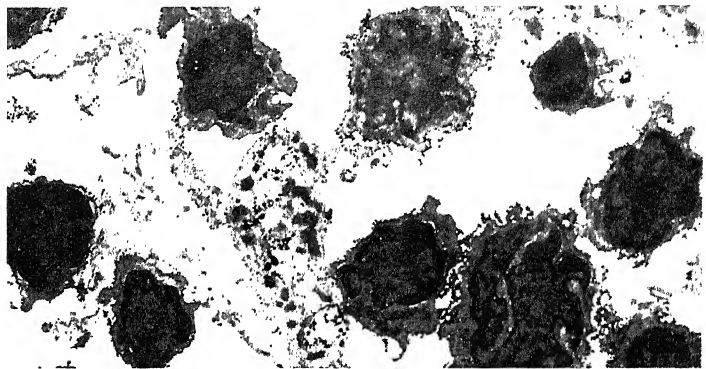
10.9D Lymphocytes in the interfollicular region of human palatine tonsil expressing LFA-1 (black dots) on their cellular membranes. Immunoelectron microscopy. Incubation with mAb to LFA-1. Magnification × 4 000.

not constitutively adhesive they become highly adhesive after cell activation and therefore play a key role in the events required for cell migration. The β2 subfamily comprises three molecules with common β2 subunit (CD18) and with chains of different molecular weight (CD11a, b, c) (Cronstein & Weissman 1993).

The CD11a/CD18 integrin molecule is known as the lymphocyte function-associated antigen 1 (LFA-1) and is present on the surface of all leucocytes (10.9D). The endothelial ligands for LFA-1 are the intercellular adhesion molecules 1 and 2 (ICAM-1 and ICAM-2) which belong to the immunoglobulin superfamily. The other two integrins of the β2 subfamily are CD11b/CD18 (Mac-1, CR3) and the less well-characterized CD11c/CD18. These molecules have more limited distribution on neutrophils, monocytes and

natural killer cells and they mediate adhesion of leucocytes to endothelium by binding to ICAM-1. Recently, monoclonal antibodies directed against integrin-mediated adhesion have been administered in studies aimed to decrease inflammatory responses (Jasin et al 1992).

Immunoglobulin supergene family

Three members of this large family of proteins are involved in leucocyte-endothelial adhesion. They are the integrin counter-receptors ICAM-1 (CD54), ICAM-2 and VCAM-1, found on the endothelial cell membrane.

The ICAM-1 has five immunoglobulin-like domains and the ICAM-2 has only two. Both the ICAM-1 and ICAM-2 are constitutively expressed on endothelium and ICAM-1 is also present on activated B cells and follicular dendritic cells in germinal centres (Springer 1990). The
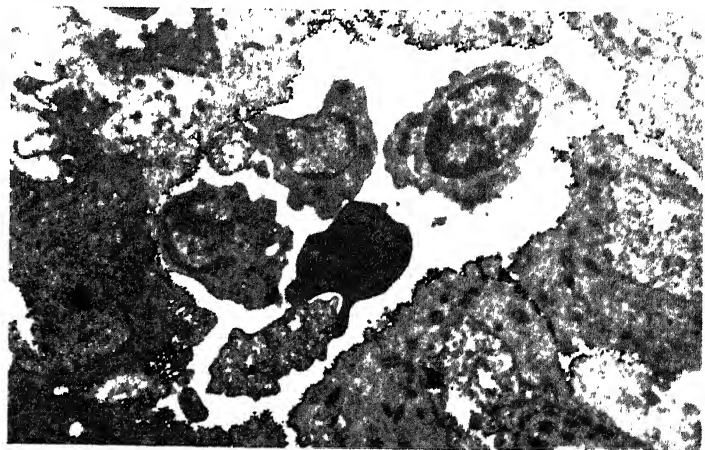
10.9E Transversely sectioned tonsillar HEV stained strongly with anti-ICAM-1 antibody on luminal and lateral (black dots), but not on the abluminal, surfaces of high endothelial cells. Immunoelectron microscopy. Incubation with mAb to ICAM-1. Magnification × 5 000.

known ligands for ICAM-1 are LFA-1 and Mac-1 integrins, whereas the ICAM-2 binds only to LFA-1. Furthermore, the expression of ICAM-1 is readily upregulated by inflammatory cytokines (10.9E) resulting in an increased binding of circulating lymphocytes and monocytes to the stimulated endothelium.

The last member of the immunoglobulin superfamily is the VCAM-1 molecule containing either six or seven immunoglobulin-like domains. Its ligand on the leucocytes is the VLA-4 integrin (Cronstein & Weissmann 1993). Although VCAM-1 is absent from resting endothelium its expression can be induced by cytokines. Thus, VCAM-1 is thought to promote an accumulation of mononuclear cells at sites of inflammation (Shimizu et al 1992; Picker & Butcher 1992).

In addition, the widely expressed cell surface molecule CD44 has been identified as a homing receptor of haematopoietic cells. The CD44 molecule is a highly gly-

cosylated protein and the major receptor for hyaluronic acid. It has been proposed by Günther et al (1991), that CD44 isoforms may play an important role in organ specific recognition, cell motility and invasion mechanisms.

In summary, the process of adhesion of leucocytes to endothelium is believed to involve multiple receptor–counterreceptor (ligand) interactions. This 'adhesion cascade' requires a co-ordinated sequence of adhesion molecules expression on both the leucocytes and the endothelium, from the time of the initial attachment to the final step of extravasation into the surrounding tissue (Shimizu et al 1992; Tanaka et al 1993).

The first step in this cascade is the loose binding, 'rolling' or 'tethering' of leucocytes, which is initiated via P- or E-selectin. Coexpression of tethering and 'signalling' molecules on activated endothelial cells, such as P-selectin and PAF and E-selectin and IL-8, augments this

initial interaction (Zimmerman et al 1992). The second step is referred to as 'triggering', in which a signal delivered to leucocytes converts the functionally inactive integrin molecules into active adhesive configurations. The third step represents the establishment of strong adhesion mediated by integrins expressed on leucocytes, binding to their endothelial ligands. The fourth and last step is the migration of leucocytes into the surrounding tissue. This step requires reduction in adhesion and 'shedding' of some molecules from the surface of leucocytes, followed by cell movement. The precise mechanisms involved in this process are as yet unknown (Hogg 1992; Shimizu et al 1992; Tanaka et al 1993).

An understanding of molecules that mediate cellular interactions in homing of recirculating lymphocytes and during the initial stages of inflammation may eventually lead to the development of a new generation of anti-inflammatory agents.

STRUCTURE OF BLOOD VES:

Sharp distinctions of blood vessels based on the structure of the wall are to some extent arbitrary, because the variations along the vascular tree are continuous. Nevertheless a few basic patterns can be identified, and are described here as different vessel types.

LARGE ELASTIC ARTERIES (10.4A, B, 11A)

The intima is made of an endothelium, resting on a basal lamina, and a subendothelial layer. The endothelial cells are flat, measuring between 1.0 and 0.2 μm in thickness, polygonal in outline and elongated with the long axis parallel to the direction of blood flow. The subendothelial layer is well developed, contains elastic fibres and collagen fibrils and small cells identified as muscle cells or muscle cell precursors and fibroblasts. The orientation of subendothelial cells is irregular but predominantly longitudinal.

In the human aorta at birth, the endothelium adheres to the internal elastic lamina. After birth the intima grows in thickness with the appearance of a subendothelial layer (subendothelial intima), composed of delicate elastic fibres and smooth muscle cells running longitudinally, intermingled with abundant ground substance, a small amount of collagen and occasional fibroblasts. Splitting of the inner elastic lamina is not uncommon. The thickening of the intima progresses with age and is more marked in distal than in the proximal segment of the aorta. The cells of the subendothelial layer are thought to migrate from the media across the inner elastic lamina.

Between the intima and the media lies a prominent inner elastic lamina. This lamina is smooth, measures about 1 μm in thickness, and is stretched under the effect of the pulse, recoiling elastically afterwards; it coils up into a serpentine outline when the vessel is completely emptied, a condition that does not normally occur in vivo. Even when empty a large elastic artery does not completely collapse.

The media has a markedly layered structure, being made of layers of elastic material (elastic lamellae) alternating with interlamellar zones made of muscle cells, collagen and elastic fibres. The arrangement is very regular and each elastic lamella with an adjacent interlamellar zone is regarded as a 'lamellar unit' of the media. In the human aorta there are approximately 52 lamellar units, measuring about 11 μm in thickness. A similar arrangement exists in all mammals, and the number of lamellar units is roughly proportional

to the vessel diameter in different species and vessels (Wolinsky & Glagov 1967b). Number and thickness of lamellar units increases during development. At birth the aorta has about 40 lamellar units. However, the developmental increase in vessel diameter far exceeds the increase in number of lamellae and in the thickness of the wall.

In the media of the largest arteries such as the aorta some authors distinguish an internal layer of musculature, situated externally to the inner elastic lamina, with muscle cells of various orientations intermingled with elastic fibres running longitudinally.

The adventitia is well developed. In addition to collagen and elastic fibres, it contains fibroblasts (which are flattened and have extremely long and thin laminar processes), macrophages and mast cells. The vasa vasorum are usually confined to the adventitia, where there are also nerve bundles, which do not come close to muscle cells, and lymphatic vessels.

MUSCULAR ARTERIES

These include vessels of a large range of sizes, and they are characterized by the predominance of muscle in the media. The intima is made of an endothelium resting on a basal lamina (10.5, 11B). The inner elastic lamina is thin, and is occasionally absent. In the media about ¾ of the mass is represented by muscle cells. Therefore, the relative amount of extracellular space is less than in large arteries, but elastic fibres, running parallel to or at a very small angle with the muscle cells, remain prominent.

ARTERIOLES (10.10)

The endothelial cells are smaller than in large arteries; their nucleated portion is thicker and often projects markedly into the lumen. Even when fixed fully distended, the endothelium of arterioles has variable thickness and displays longitudinal grooves and ridges. The nuclei are elongated and oriented parallel to the vessel length and so is the long axis of the cell.

The abluminal surface of the endothelium is lined by a basal lamina, but an inner elastic lamina is absent or barely recognizable. When present, the elastic lamina is amply fenestrated and is traversed by cytoplasmic processes of muscle cells or of endothelial cells.

The muscle cells are larger in volume than those of large arteries and they form a layer one cell thick. They are arranged circumferentially and are tightly curved and wound around the endo-

10.10 Transmission electron micrograph of a partially contracted small arteriole in transverse section, showing an outer zone of non-striated myocytes and an inner lining of endothelial cells. Erythrocytes are visible within the lumen. The specimen is from the uterus of a rat. Magnification × 4000. (Supplied by Dr Gail ter Haar.)
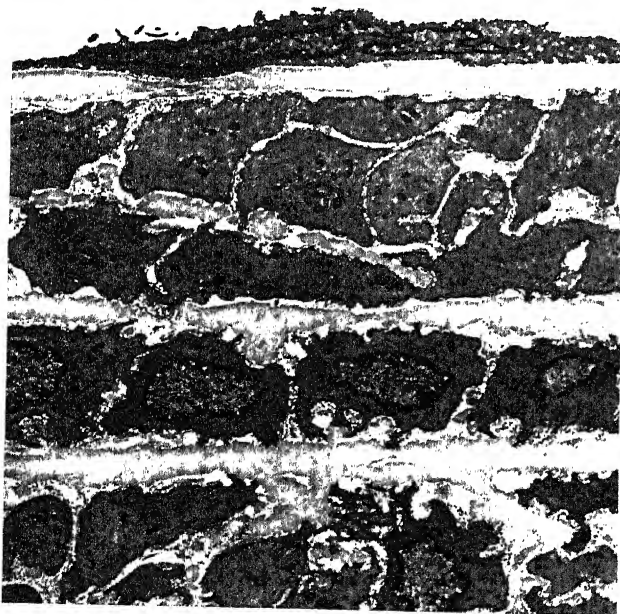
10.11A Elastic artery sectioned longitudinally and examined by electron microscopy. Beneath the endothelium (*at top*) with the nucleated profile of a flat endothelial cell, is a thick inner elastic lamina. In the media (not shown in its full thickness) are several muscle cells profiles in transverse section, some nucleated, separated by large elastic fibres and elastic lamellae. Note the irregular, convoluted shape of the muscle cell surface. Magnification × 4500.

10.11B Muscular artery sectioned longitudinally and examined by electron microscopy. Beneath the endothelium (*at top*) with the nucleated profile of a flat endothelial cell, is an inner elastic lamina. In the media are several muscle cells profiles in transverse section; they are closer to each other than in the elastic artery, and the intervening spaces are occupied by collagen fibrils. In the bottom part of the micrograph is the tunica adventitia with fibroblasts and collagen fibrils. Magnification × 4500.

thelium (**10.8**). In the smallest arterioles each cell makes several turns, producing extensive apposition between parts of the same cell. The muscle cell profiles are asymmetric in that the region of the cell membrane nearest the adventitia bears most of the dense bands, hence most of the insertions of myofilaments.

The *precapillary arteriole* (strictly speaking, however, all arterioles are pre-capillary), or *precapillary sphincter*, has been variously defined in the literature. The most acceptable definition is that the precapillary sphincter is that part of the arteriole where the most distal muscle cell is found, before the vessel opens into the capillary network (Wiedeman et al 1976). The functional interest in the precapillary sphincters is that they appear to be mainly under myogenic, rather than under nervous control. Because of their position they are regarded not so much as sites of regulation of peripheral resistance but rather as sites where the blood flow into the capillary network is monitored (Wiedeman et al 1976).

Arterioles are usually densely innervated by sympathetic fibres, via small nerve bundles containing axons expanded in varicosities and packed with axonal vesicles, mostly of the adrenergic type. The distance between axonal membrane and muscle cell membrane can be reduced to 50–100 nm and the gap is occupied by a single basal lamina. Ultrastructural studies with serial sections have shown that these contacts between adrenergic axons and muscle cells (autonomic neuromuscular junctions) are very common in arterioles (Luff et al 1987).

CAPILLARIES (10.12, 13)

The wall of capillaries is made of an endothelium and its basal lamina, plus a few isolated pericytes (see p. 1459). The capillaries are the vessels closest to the tissue they supply and their wall is in intimate relation with the tissue. Their structure varies in different locations. They measure 5–8 μm in diameter (and much more in the case of sinusoids) and are hundreds of microns long. Their lumen is just large enough to let blood cells through, one at a time and with considerable deformation of their shape. It has been pointed out, however, that the vascular lumen is not at its narrowest in capillaries: the true bottleneck of the circulatory system is at the level of the arterioles (Cliff 1976), where muscle contraction can obliterate the lumen.

Commonly, a single endothelial cell forms the outline of a capillary and then the junctional complex (see p. 1457) occurs between laminar extensions of the same cell. In some capillaries, usually near their venous end, there are 'seamless' endothelial cells, i.e. the lumen is a large membrane-bounded canal through the cytoplasm (Bär et al 1984): in this case the lumen probably originated by fusion of several intracellular vacuoles (Wolff et al 1975).

The structural characteristics of endothelial cells are discussed on page 1456. In capillaries the endothelium is at its thinnest: 2–3 μm at the level of the nucleus, and down to as little as one-fifth of a micron in certain regions. The endothelial cells of some capillaries have *fenestrations*, or pores, through their thinnest portions. Fenestrations are approximately circular, 50–100 nm in diameter, and at their edge the luminal and the abluminal membranes of the endothelial cell come into contact with each other. The fenestration, or fenestra, itself is usually occupied by a thin electron-dense diaphragm resembling in appearance a thin basal lamina. The chemical composition of endothelial fenestrae is still unknown. Permeability studies
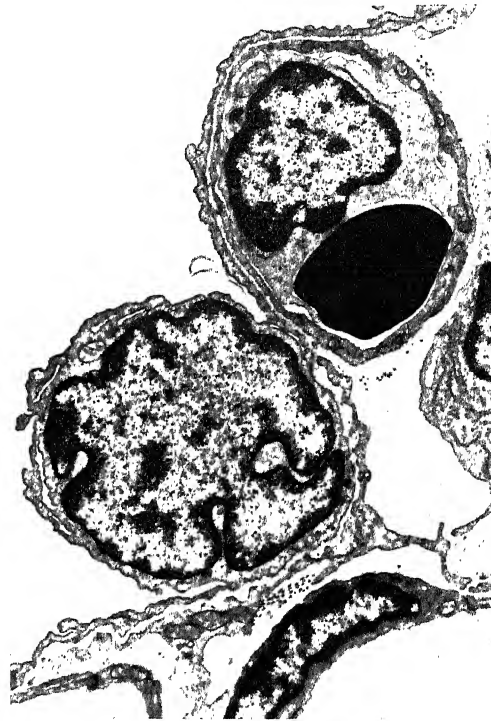
10.12A To the right a blood capillary in the wall of a pulmonary alveolus. The lumen of the capillary is occupied by a red blood cell and a lymphocyte. Lower centre is a Type I pneumocyte with its nucleus and with slender cytoplasmic processes fully lining the lumen of the air-filled alveolus (*top left*). Two other capillaries are partially visible at the bottom; their lumen is occupied by plasma. Magnification × 8 000.
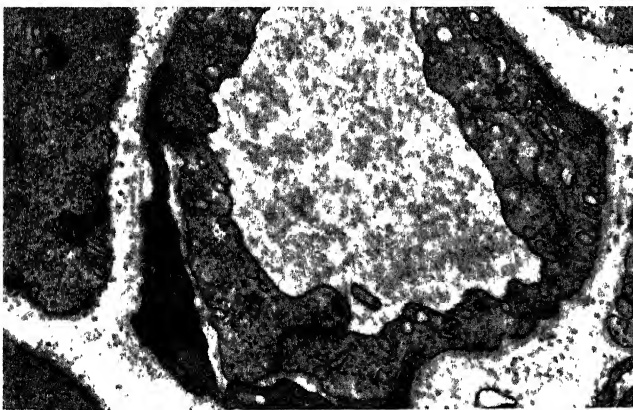
10.12B Intramuscular blood capillary. The endothelial cell to the left shows the nucleus; at top and bottom are junctions with another endothelial cell. The lumen of the capillary is occupied by a red blood cell and plasma. On the outer surface is a basal lamina and (*at bottom*) a slim process of a pericyte. Magnification × 10 000.
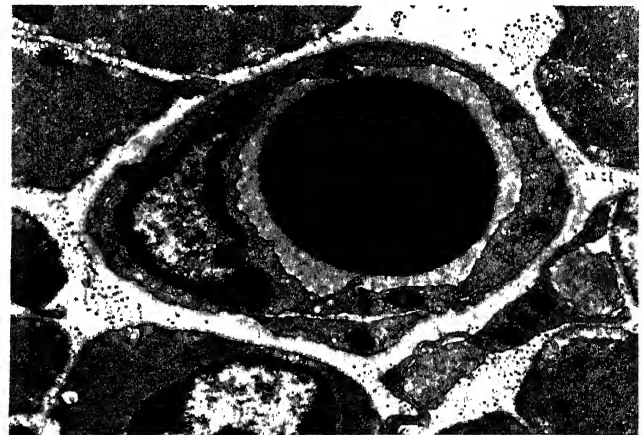
10.12c Intramuscular blood capillary. Caveolae are visible on both the lumenal and the abluminal surfaces of the endothelial cell, together with endoplasmic reticulum, microtubules and bundles of microfilaments. The edges of the cell are in contact with each other at the bottom, and they form specialized junctions. Magnification × 29 000.

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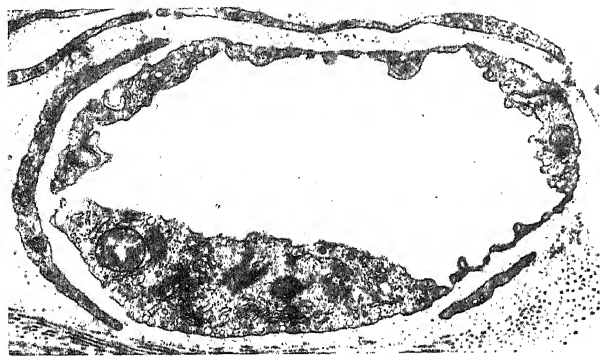
10.13A A fenestrated capillary, surrounded by a basal lamina, a laminar process of a pericyte (*left*) and collagen fibrils (*bottom*). The endothelial cell at top contains various organelles, including two centrioles, vesicles and Golgi complexes. Magnification × 18 000.
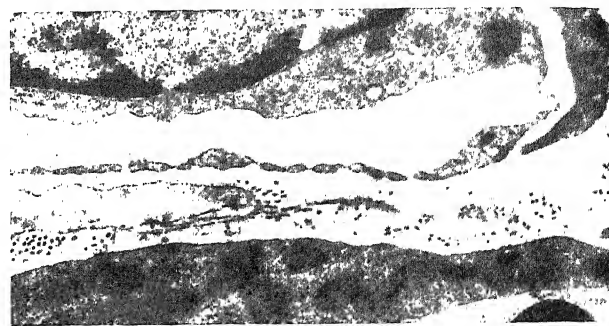
10.13B A fenestrated capillary in the intestinal mucosa. The fenestrations are close to the basal surface of the lining epithelium. Note the basal lamina on both the epithelial and the endothelial cell and the intervening collagen fibrils and fibroblastic process. Magnification × 30 000.

have shown that other components in addition to the diaphragm control the permeability of a fenestra (Levick & Smaje 1987). These capillaries are known as *fenestrated capillaries*, and they are found in renal glomeruli, in intestinal mucosa (10.13) and in endocrine and exocrine glands. Fenestrations are also almost invariably present in capillaries lying close to an epithelium, including skin (Imayama 1981).

Capillaries without fenestrations are known, somewhat inaccurately, as *continuous capillaries*. Capillaries in the brain, in striated and smooth muscles, in lung and in connective tissue are of this type. Capillary permeability varies greatly among tissues and can be correlated partly with the local type of endothelium. In tissues where large molecules pass easily (e.g. alimentary tract, endocrine glands) fenestrated endothelia exist, with numerous caveolae; intercellular junctions are either incomplete or 'leaky'. Where barriers to diffusion of large molecules occur (e.g. brain, thymic cortex and testis), endothelia are complete and not fenestrated, with efficient zonula junctions of the occludens type between cells; here, caveolae are somewhat fewer in number. Other tissues (e.g. skeletal muscle) show an intermediate condition.

Sinusoids. These are capillaries, large and irregular in shape, which have true discontinuities in their wall: blood can diffuse out of the circulation with only a minimal hindrance. A basal lamina may be found over these slits or holes in the endothelium, and other cell types may be found in the perisinusoidal space. Sinusoids occur in large numbers in the liver, spleen, bone marrow and adrenal medulla.

VENULES

Postcapillary venules are essentially tubes of flat, oval or polygonal endothelial cells supported by basal lamina and a delicate adventitia of collagen fibres mainly running longitudinally and fibroblasts (Rhodin 1968). They lack a distinct elastic lamina. Pericytes often accompany these venules. Postcapillary venules are sites of fluid exchange and leucocyte migration; in venules of lymphoid tissue of the gut and bronchi and in the lymph nodes and thymus, endothelial cells are taller and have intercellular junctions through which lymphocytes and other blood components can readily pass (see p. 1432). In other tissues these vessels are believed to be a major site of migration of neutrophils, macrophages and other leucocytes into extravascular spaces, and also a region of temporary endothelial attachment for neutrophils, forming marginated pools of these cells (see p. 1403).

The intracellular junctions of venules are sensitive to inflammatory agents which increase their permeability to fluids and defensive cells thus facilitating extravasation (see, e.g., Marchesi 1961, 1962). In general, the endothelium of venules has fewer tight junctions, and is more permeable. For example, in neurogenic inflammation venules are the primary site of extravasation of plasma.

When two or more capillaries converge the resulting vessel is larger (up to 30 μm), and is known as a *venule* (or a *postcapillary venule*). Venules do not acquire musculature until, after further convergence, they are about 30 μm in outer diameter, when they are known as *muscular venules* (10.14). The distinction is important because postcapillary venules are as permeable to solutes as capillaries, and are thus part of the microcirculatory bed. At the level of the postcapillary venule the cross-sectional area of the vascular tree is at its maximum, and there is a dramatic fall in pressure, from 25 mmHg in the capillary to about 5 mmHg (Rothe 1983). Muscular venules converge into *collecting venules* which lead to a series of veins of progressively larger diameter. Venules and veins are capacitance vessels (see p. 1453).

VEINS

Veins are characterized by a relatively thin wall in comparison with arteries of similar size and by a large capacitance. A small increase in lumenal pressure produces a large increase in volume, although the pressure volume relation is not linear. The wall thickness is not exactly correlated to the size of the vein, but it varies in different districts: for example, the wall is thicker in veins of the leg than in veins of similar size in the arm (Kügelgen 1955).

The amount of muscle is considerably less than in arteries, while collagen and, in some veins, elastic fibres are the predominant components. In the cadaver the veins, even when collapsed, maintain their large diameter and they are more likely to be found full of blood than are the arteries. Furthermore, tethering of some veins to connective tissue fasciae and other surrounding tissues may prevent collapse of the vessel even with a negative transmural pressure.

Pressure within the venous system does not normally exceed 5 mmHg, it decreases centripetally as the veins grow larger and fewer in number, and it approaches zero in the proximity of the heart. Because of the small amount of musculature veins have limited influence on blood flow. However, during a sudden fall in blood pressure following a haemorrhage, elastic recoil and reflex constriction in veins compensate for the blood loss and tend to maintain venous return to the heart. Krogh (1959) stressed the importance of the active venous return by pointing to the fact that in man the heart is at a greater height above the feet than in any other mammal, except the elephant and the giraffe. Vasoconstriction in cutaneous veins in response to cooling is important in thermoregulation.

The structural plan of the wall is similar to that of other vessels, but the division into layers, especially media and adventitia, is often not clearly seen. The lumen is lined by an endothelium which lies over a basal lamina. A distinct inner elastic lamina is not found. The musculature is much thinner and has a more irregular distribution than in arteries. The orientation of muscle cells is not uniform and often variable and irregular. In most veins (for example those of the arm and leg) the musculature is arranged approximately circularly. Longitudinal musculature is present in the iliac vein,

10.14 A venule transversely sectioned and examined by electron microscopy. One of the endothelial cell profiles is nucleated and the lumen contains an erythrocyte. The tunica media consists of a single layer of muscle cells running almost circumferentially. To the bottom right is a nerve bundle. Magnification × 11 000.

brachiocephalic vein, superior vena cava, inferior vena cava, portal vein and renal vein. In the renal vein and in parts of the inferior vena cava, virtually all the musculature is arranged longitudinally (Kügelgen 1955). Large veins entering the heart are encroached upon for a short distance by myocardial tissue, and in the coronary sinus this covering is complete (Coakley & King 1959); in the transition areas smooth and cardiac muscle lie side by side. Muscular tissue is absent in certain veins: the maternal placental veins, the dural venous sinuses and pial veins, the retinal veins, the veins of trabecular bone and the venous spaces of erectile tissue. Such veins consist of endothelium supported by variable amounts of connective tissue.

In the outer layer of connective tissue there are few nerve fibres, vasa vasorum and abundant elastic fibres. Overall, collagen is the main component of the venous wall in man, accounting for more than half its weight. Walls of the larger veins, like the arteries, are supplied by vasa vasorum but these in veins may penetrate the wall deeply, perhaps because of the lower oxygen tension. Postganglionic sympathetic efferent and primary afferent nerves are distributed to the veins, as in arteries, but less abundantly.

Most veins have valves to prevent reflux of blood (10.15). A valve is composed of an inward projection of the tunica intima, strengthened by collagen and elastic fibres and covered by endothelium differing in orientation on its two surfaces. Surface cells which are juxtamural are transversely arranged whereas on the luminal surface, over which the main stream of blood flows, cells are arranged longitudinally in the direction of the current. Most commonly, two such valves lie opposite one another, especially in smaller veins or in larger ones where smaller tributaries join; occasionally three valves lie in opposition, sometimes only one is present. The valves are semilunar (cusps) and attached by convex edges to the venous wall; their concave margins are directed with the current and apposed to the wall as long as flow is towards the heart, but when blood flow reverses the valves close. Centripetal to each valvular flap the wall is expanded into a sinus, which fills when blood flow is reversed against a closed valve, giving a 'knotted' appearance to the distended veins, if these have many valves. In the limbs, especially the legs where venous return is against gravity, such valves are of great importance to venous flow, as blood is moved towards the heart by the intermittent pressure produced by contractions of the surrounding muscles. Valves are absent in very small and in very large veins and in many tissues are rare or absent. Valves are absent in veins of the thorax and abdomen.

Special features are found in some veins such as the portal vein, where there is a prominent musculature made of a thick outer layer arranged longitudinally and mixed with abundant connective tissue (Ferraz de Carvalho & Rodrigues 1978) and a thin inner layer arranged as a low-pitched helix that is almost circular.

VASCULAR SHUNTS

These are communications between arteries and veins found in many regions of the body where the capillary circulation is bypassed by wider channels. They may be classified according to their dimensions, site and complexity as:

- preferential thoroughfare channels
- 'simple' arteriovenous anastomoses
- specialized arteriovenous anastomoses or *glomera*.

Preferential 'thoroughfare' channels

In many tissues true capillaries arise not only as direct side branches of terminal arterioles but also as side branches of a main or 'thoroughfare' channel connecting the terminal arteriole and the venule (Maggio 1965; Grant & Wright 1968, 1970; Zweifach 1973). This *thoroughfare channel* has a larger calibre than true capillaries and in ultrastructure resembles typical continuous capillaries, except that widely spaced smooth muscle cells spiral round the endothelium. Each capillary side branch has at its origin a precapillary sphincter. Such a channel and its capillaries form a functional *microcirculatory unit* (10.16). When functional demand is low, blood flow is largely limited to the bypass channel, with most precapillary sphincters closed. Periodic opening and closing of different sphincters may irrigate different parts of the capillary net. With increasing demand, blood flow may increase greatly following the opening of many sphincters. The size of the microcirculatory unit varies greatly, for example in skeletal muscle each channel gives rise to 20–30 true capillaries, but in some glandular tissues only one or two may be given off. Detailed investigations in the cremaster muscle and biceps femoris tendon of the rat (Grant & Wright 1968, 1970) have shown that in these sites, bypass channels are confined to perimuscular and peritendinous connective tissues and absent from the muscles itself. The form of the capillary net also varies with the tissue meshes being either round or elongated. Round or angular meshes are most common and prevail where networks are dense, as in the lungs, mucous membranes and skin. Elongated meshes occur in muscles and nerves, aligned parallel with their fibres. Sometimes capillaries are looped, as in the papillae of the skin and tongue. The number of capillaries and the size of their mesh determine the degree of vascularity; the smallest meshes occur in the lungs and the choroid of the eye.

Arteriovenous anastomoses (10.17)

Arteriovenous anastomoses are direct connections between smaller arteries and veins (Grant & Bland 1931; Popoff 1934; Clark 1938). Connecting vessels may be straight or coiled, often possessing a thick muscular tunic and a narrow lumen, about 10–30 μm across. Under sympathetic control through abundant non-myelinated fibres in its wall, the vessel is able to completely close, circulation being then via
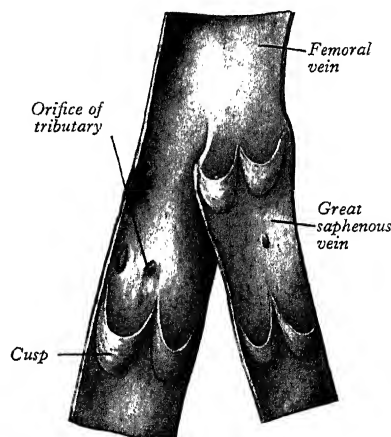
10.15 The upper portions of the femoral and great saphenous veins laid open to show the valves. About two-thirds of the natural size.
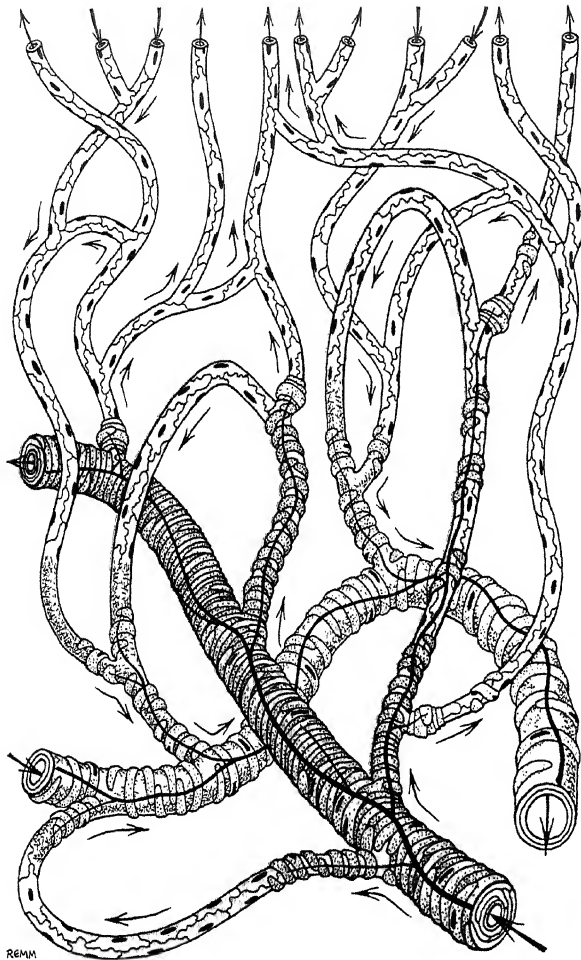
10.16 Diagram of a microcirculatory unit based upon descriptions in Zweifach (1959, 1961, 1973) and Reynolds and Zweifach (1959). Note the terminal arteriole, thoroughfare channels, capillaries and collecting venule. The distribution of smooth muscle cells and precapillary sphincters is shown.
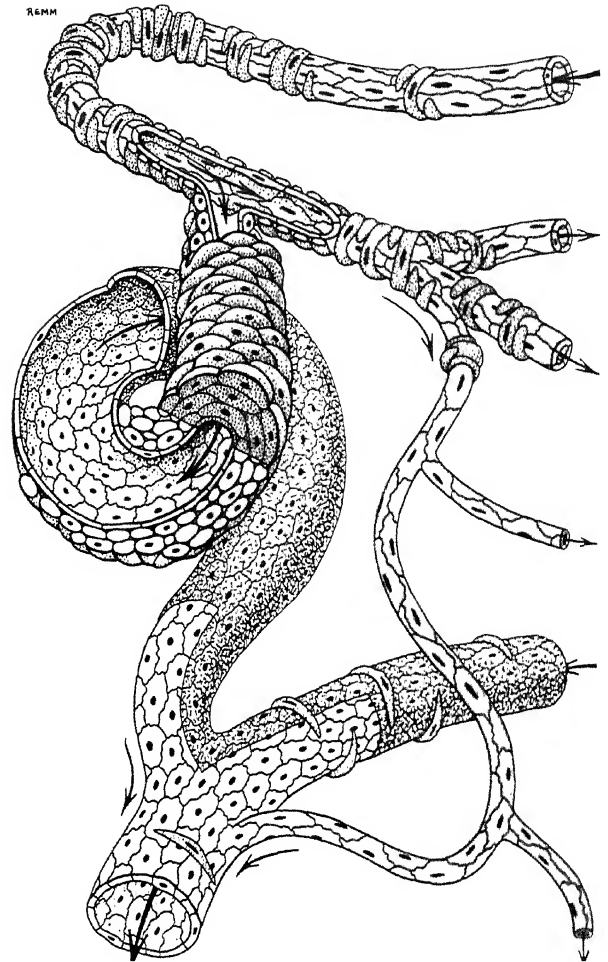
10.17 Diagram of an arteriovenous anastomosis. Note the thick wall of the anastomotic channel composed of layers of modified smooth muscle cells.

the capillary bed. When patent, the vessel carries blood from artery to vein, partially or completely excluding the capillary bed from the circulation.

Arteriovenous anastomoses of relatively simple type occur in the nasal, labial and aural skin, nasal and alimentary mucous membranes, coccygeal body, erectile tissue, tongue, thyroid gland, sympathetic ganglia and probably elsewhere. Their ultrastructure has been investigated by Cauna (1970).

In the skin of the hands and feet (especially digital pads and nail beds) anastomoses form a large number of small units termed 'glomera'. They are deep in the corium and each 'glomus' has one or more afferent arteries, stemming from branches of cutaneous arteries approaching the surface (10.17, 18). These afferents arise at right angles from their parent vessels which then continue into the dermal papillary layer, ending in a capillary plexus. A short distance from its origin an afferent artery gives off a number of fine 'periglomeral' branches and then immediately enlarges, makes a sinuous curve and narrows again into a short funnel-shaped vein opening at right angles into a collecting vein. This vein commences on the deep aspect of the glomus, curving round its superficial surface, whence it retraces its course, receiving venules from the dermal papillary layer. Finally, it joins a deeper cutaneous vein.

In the newborn child arteriovenous anastomoses are generally few and poorly differentiated, but they develop rapidly during the early years of life. In old age they atrophy, sclerose and diminish in number.

The vessels concerned in digital arteriovenous anastomoses are

unusual (10.18). Where these enlarge the afferent artery has small luminal endotheliomuscular projections but proximal to this structure it is typical. The connecting vessel has an endothelium supported by fine collagenous fibres but no internal elastic lamina. Longitudinal and circular muscle layers are not sharply differentiated but the muscular wall is thick; in sections myocytes appear pale and swollen, with central nuclei, and hence described as 'epithelioid'. The efferent vein has a thin wall lacking muscle but containing many elastic fibres which pass into the tunica adventitia of the collecting vein.

The mechanisms by which arteriovenous anastomoses regulate local flow are poorly understood. Where they have circular muscle in their walls, epitheliocytes may help to narrow the lumen; where it is absent closure may be due to swelling of these epithelioid cells. Cutaneous arteriovenous anastomoses are essential to the control of general and local body temperature. When a rabbit's ear is raised above 40°C, muscle in the walls of the connecting vessels relax and increased blood flow at body temperature results, with a consequent cooling. When the local temperature is lowered below 15 C, the connecting vessels again relax and increased flow at body temperature then helps to raise local temperature, unless artificial cooling is intensified. When the animal's overall body temperature is raised experimentally, a general opening of all subcutaneous arteriovenous anastomoses results, with an increase in heat radiation and consequent drop in body temperature (Grant 1930). The cooling effect of panting in dogs also involves the opening of lingual arteriovenous anastomoses. The paucity and immaturity of arteriovenous anastomoses in the newborn and marked reduction in subcutaneous
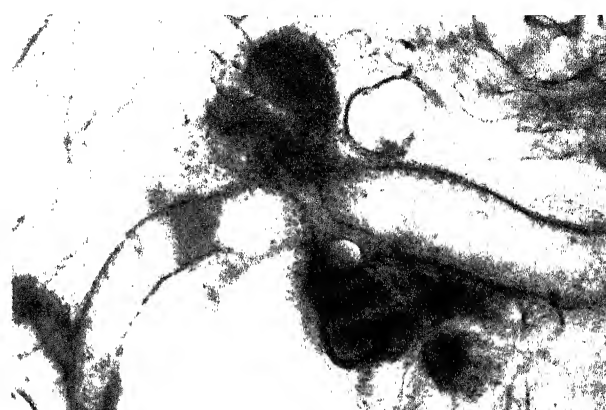
10.18 Human digital arteriovenous anastomoses prepared by intravascular perfusion of haematoxylin and subsequent clearing of a full thickness specimen of skin. The heavily stained, thick-walled, tortuous, anastomotic channels contrast with the central arterial stem and the thin-walled venous outflow channels. See text for further details. (The specimens were prepared and provided by R T Grant, Guy's Hospital Medical School.)

arteriovenous anastomoses with advancing years may be related to observed less efficient temperature regulation in these two extremes of age.

Arteriovenous anastomoses in alimentary mucous membranes fulfil a different function (Spanner 1932). An arteriole to a human villus has a direct connection with its corresponding venule and when absorption is in abeyance the connection is patent and helps to raise portal venous pressure; during alimentary absorption the anastomosis is closed and consequently blood traverses the capillary plexus.

Other suggested functions of arteriovenous anastomoses include regulation of blood pressure, secretion by epithelioid cells and pressor reception.

Some of the nourishment of the tissues of the vessel wall is provided by diffusion from the blood circulating in the vessel itself. In addition, large vessels have their own vascular supply, a network of small vessels, mainly microcirculatory vessels, the vasa vasorum. The wall thickness at which simple diffusion from the lumen becomes insufficient is about 1 mm (Kirk & Laursen 1955). The vasa vasorum originate from, and are drained into, adjacent vessels, which are peripheral branches of the vessel they supply. They are spread within the adventitia and, in the largest of arteries, penetrate into the outermost part of the media. The depth of penetration of capillaries into the media depends on the thickness of this tunica. Wolinsky and Glagov (1967b) in a comparative study of several mammals, found that only lamellar 'units' in excess of 29 are vascularized: if there are less than that number of units, the media remains avascular, and in the other cases the innermost 29 lamellae remain avascular.

INNERVATION OF BLOOD VESSELS

Blood vessels are innervated by efferent autonomic fibres, which regulate the contraction of the musculature, i.e. diameter and tone of the vessels, notably the arteries. In addition, most arteries also provide 'routes' along which nerves both travel to peripheral organs and arborize within them. These are paravascular nerves and they do not provide innervation to the vessel itself. They are parallel to the vessel but are situated at some distance from its adventitia and nerve and vessel are topographically but not physiologically related. In contrast, perivascular nerves run in the adventitia of the artery, where they branch and anastomose, forming a meshwork around the vessel. These nerves travel a long distance along the vessel, and they can provide innervation to its musculature. They are small bundles of axons, and the axons are almost invariably unmyelinated and typically varicose. Most of them are postganglionic fibres issuing from sympathetic ganglion neurons. However, some perivascular fibres originate from cranial parasympathetic ganglia and from ganglia of the enteric submucosal plexus, and some brain vessels are innervated by neurons of the central nervous system. The density of innervation varies in different vessels and in different areas of the body. The innervation is sparser in veins, where the musculature is consistently less well developed than in arteries, and the same is true of lymphatic vessels. But large veins with a conspicuous musculature, such as the portal vein, are richly supplied with nerves.

The principal site of action of nerves of blood vessels is on muscular artery and especially arterioles. The main effect of nerves is vasoconstriction and increase in vascular tone, and this role is particularly effective in arterioles, on account of their dense innervation and of the mechanical gain derived from the high ratio of wall thickness to vessel radius. Adrenergic fibres are vasoconstrictor and they act on adrenoceptors—of which several types are known—in the muscle cell membrane. Other substances are released with noradrenaline by the activated nerve endings, allowing for a complex regulation of the neurogenic control of vasomotility. The mechanical activity of vascular musculature is also under the influence of circulating factors such as hormones. In addition, there are factors, such as nitric oxide and endothelins, which are released from the endothelial cells and have a potent effect on vascular muscle cells. In this multiple control, while neurotransmitters reach the musculature from the adventitial surface of the media, the endothelial factors diffuse from its intimal surface. In some areas there are also sympathetic cholinergic fibres which inhibit muscle activity and induce vasodilatation. Afferent fibres from dorsal root ganglia are present in some vessels and can be identified either histochemically or with retrograde tracer studies. These afferent fibres usually end with a long chain of varicosities, but the physiology of their sensory transduction in the vessel wall is still obscure.

The terminal portions of the axons found in the vascular adventitia is varicose, i.e. it has a beaded appearance with expanded bulbous portions (up to 1.5 μm in diameter) and narrow intervaricose segments (about 0.2 μm in diameter). Varicosities contain mitochondria, microtubules, some neurofilaments and, above all, axonal vesicles, which transport and release the neurotransmitters. The intervaricose segments are occupied almost exclusively by a few microtubules.

All the perivascular fibres are confined to the adventitia of the vessel, where they run amid collagen fibres, fibroblasts and small vessels (lymphatics and vasa vasorum). Only in some large muscular arteries, small nerve fibres are occasionally found within the outermost layers of the musculature. As a general rule, nerve fibres do not penetrate into the media, and they are never found in the intima. (Nerve fibres are sometimes close to the wall of capillaries, and the possibility of a physiological interaction between nerve endings and

endothelial cells cannot be ruled out.) Because of their location in the adventitia, nerve fibres run at a considerable distance even from the nearest muscle cell. In large muscular arteries many varicosities lie more than 1 μm away from the nearest muscle cell and any neuromuscular transmission requires diffusion of neurotransmitters over a considerable distance. In smaller vessels, such as arterioles, however, where the elastic and collagen material is less abundant, axonal varicosities lie within a few tens of nanometres from muscle cells. These points of close apposition are regarded as proper neuromuscular junctions, and, when the tissue is examined in serial sections, they appear quite numerous (Luff et al 1987).

Some tissues lack vascularization, for example cartilage, epithelia even when thick and stratified, the media of vessels themselves and elastic tissue in general. This may be partly due to an active inhibition of vascular growth by certain tissues.

Angiogenesis is the formation of new vessels starting from pre-existing vessels, during growth of an organ, both in development and in hypertrophy and also in pathological tissues as in tumours.

The existence of diffusible angiogenic factors is well documented and some angiogenic polypeptides have been isolated and sequenced, including some growth factors (Folkman & Klagsbrun 1987). One of the trophic factors that stimulates migration and division in endothelial cells is b-FGF (Tsuboi et al 1990). Interestingly, the endothelial cells themselves express the b-FGF gene and release b-FGF; this raises the possibility that endothelium regulates its own growth via this trophic factor (Schweigerer et al 1987).

New capillaries originate from sprouting of small venules (Ausprunk & Folkman 1977); there is a local disruption of the basal lamina followed by migration of endothelial cells. The sprout is initially solid, but then becomes partly canalized, while it grows by division of the endothelial cells, until it joins another sprout and blood flow begins.

The importance of angiogenesis in human pathology stems from the possible role of blood vessels in the growth of tumours. Tumours implanted into isolated perfused organs in vitro fail to grow beyond a few millimetres in diameter; the same tumours reimplanted into donor mice grow to more than 1 cm³ and kill their hosts (Folkman & Klagsbrun 1987). Since only the reimplanted tumours become vascularized (Folkman & Klagsbrun 1987), the tumour growth seems to be linked to capillary growth.

THORACIC CAVITY AND HEART

The thoracic skeleton is described on pages 545–546. The volume enclosed within the thoracic cavity does not correspond with that enclosed by the osseous thorax because the lower part of the space surrounded by the bony elements is encroached upon by the diaphragm and the mobile and distensible organs within the upper abdomen. The capacity of the thoracic cavity also varies with posture and respiration, both affecting the position and relations of the thoracic organs. Its arbitrary upper limit is usually taken as the oblique plane of its inlet at the first rib, but the pulmonary apices and pleural cavities extend above this level into the neck, reaching the level of the **neck** of the rib.

UPPER OPENING (INLET) OF THORAX

The boundaries are formed by the skeleton described on page 545. The structures passing through the opening can be divided into two groups:

- those in or near the medial plane
- those on each side closely related to the cervical parts of the lungs.

Near the midline: behind the manubrium of the sternum, the lowest parts of the sternohyoid muscles enter the thorax, and behind them are the sternothyroid muscles along with vestiges of the thymus gland and the inferior thyroid veins passing down to empty into the brachiocephalic veins. In children, particularly, the left brachiocephalic vein itself may be in the thoracic inlet. **Posteriorly**, the trachea and the oesophagus, with the left recurrent laryngeal nerves, pass through the median part of the opening. The thoracic duct also passes through the opening behind the left margin of the oesophagus. Anterior to the vertebral column are the prevertebral longus colli muscles and the anterior longitudinal ligament.

On each side: the upper part of the pleura and the pulmonary apex occupy the inlet. Between the pleura and neck of the first rib, mediolaterally, are found the sympathetic trunk, the superior intercostal artery and the ventral branch of the first thoracic nerve as it passes superolaterally to join the brachial plexus. Anteriorly, the internal thoracic artery enters the thorax between the pleura and the first costal cartilage while, medial to the artery, its vein leaves the thorax.

On the right (**10.26**): the brachiocephalic artery leaves the thorax between the trachea and pleura. The vagus nerve, having passed between subclavian artery and vein, is between the pleura and the brachiocephalic artery at the inlet. The right brachiocephalic vein enters the thorax anterolateral to its artery. The right phrenic nerve crosses the internal thoracic artery and is lateral to the brachiocephalic vein behind the first costal cartilage.

On the left (**10.26**): the left common carotid and subclavian arteries leave the thorax between the pleura and trachea, the left vagus nerve descending lateral to the interval between them. Anterolateral to this is found the left brachiocephalic vein. The left phrenic nerve passing inferomedially crosses anterior to the internal thoracic artery at a higher level than the right. At the inlet, the left phrenic nerve is found between the left brachiocephalic vein anterolaterally and the subclavian and common carotid arteries posteromedially.

LOWER OPENING (OUTLET) OF THORAX

This extensive opening is wider transversely and slopes obliquely down and backwards, so that the vertical extent of the cavity is much longer posteriorly than it is anteriorly. The diaphragm (p. 815) closes the opening and forms a convex floor for the cavity. It is flatter centrally than at its peripheral attachments. It is higher on the right and, in cadavers, this side of the floor reaches the level of the upper border of the fifth costal cartilage. On the left, the diaphragm reaches only to the level of the sixth cartilage. (See p. 816 for further information on diaphragmatic shape and levels.) From the summit of each side, the diaphragm slopes abruptly down to its sternal, costal and vertebral attachments. The muscle is short anteriorly, progressively longer laterally, and it is longest and with a much more marked slope posteriorly, where the space between the diaphragm and the posterior thoracic wall narrows rapidly as it extends inferiorly.

DIVISIONS OF THORACIC CAVITY

The thoracic cavity is divided by the *mediastinum*, itself formed by the mass of structures between the lungs which extend from the sternum to the vertebral column and from the thoracic inlet to the diaphragm. The heart is in the mediastinum, enclosed by the *pericardium*. The lungs occupy the right and left regions of the thorax, each covered by a serosal membrane, the *pleura*, which also lines the corresponding half of the thorax and the lateral aspect of the mediastinum (**10.21, 24**).

For description, the mediastinum is arbitrarily divided into superior and inferior parts. The *superior part* extends from the thoracic inlet to an oblique (*transverse thoracic*) plane passing through the lower edge of the manubrium of the sternum and lower border of the fourth thoracic vertebra. The *inferior part*, below this

plane, is subdivided into an *anterior* part in front of the pericardium, a *posterior* component behind this and the diaphragm, and a *middle* component, containing the pericardium and the heart together with the large vessels entering or leaving it. Detailed accounts of the mediastinal contents are included with descriptions of the respiratory organs (pp. 1636–1646); the heart (pp. 1474–1504); and the oesophagus (p. 1751).

The pericardium contains the heart and the juxtacardiac parts of its great vessels. It consists of two components, the fibrous and the serosal pericardium. The *fibrous pericardium* is a sac made of tough connective tissue, fully surrounding the heart without being attached to it. This fibrous sac develops by a sequential process of cavitation of the embryonic body wall by expansion of the secondary pleural cavity (see p. 180); thus its lateral walls are clothed externally by *parietal mediastinal pleura*. The *serosal pericardium* consists of two sacs of serosal membrane, one inside the other, the inner (visceral) one adhering to the heart and forming its outer covering known as the *epicardium*, while the outer (parietal) one lines the internal surface of the fibrous pericardium. The two serosal surfaces are apposed and separated by a film of fluid, thus allowing movement of the inner membrane and the heart adhering to it, except at the arterial and venous areas of the pericardium where the two serosal membranes merge. The latter constitute two parietovisceral lines of serosal reflexion (see below). The separation of the two membranes of the serosal pericardium creates a narrow space, the *pericardial cavity*, which provides a complete cleavage between the heart and its surroundings thus allowing it some freedom to move and change shape.

Fibrous pericardium

The fibrous pericardium is roughly conical and clothes the heart. **Superiorly**, it is continuous exteriorly with the adventitia of the great vessels, while **inferiorly** it is attached to the central tendon of the diaphragm and a small muscular area of its left half. Above, the fibrous pericardium not only blends externally with the great vessels, but is continuous with the pretracheal fascia (p. 804). **Anteriorly** it is also attached to the posterior surface of the sternum by superior and inferior sternopericardial ligaments, although the extent of these 'ligaments' is extremely variable, the superior one often being undetectable. By these connections, the pericardium is securely anchored and maintains the general thoracic position of the heart, serving as the 'cardiac seat belt'.

Anteriorly, the fibrous pericardium is separated from the thoracic wall by the lungs and the pleural coverings. However, in a small area behind the lower left half of the body of the sternum and the sternal ends of left fourth and fifth costal cartilages, the pericardium is in direct contact with the thoracic wall. Until it regresses, the lower end of the thymus is also anterior to the upper pericardium. **Posteriorly** are the principal bronchi, the oesophagus, the oesophageal plexus, the descending thoracic aorta, and the posterior parts of the mediastinal surface of both lungs. **Laterally** are the pleural coverings of the mediastinal surface of the lungs. The phrenic nerve, with its accompanying vessels, descends between the fibrous pericardium and mediastinal pleura on each side. **Inferiorly**, the pericardium is separated by the diaphragm from the liver and fundus of the stomach.

Vessels receiving extensions of the fibrous pericardium are the aorta, the superior vena cava, the right and left pulmonary arteries and the four pulmonary veins. The inferior vena cava, traversing the central tendon, has no such covering.

Serosal pericardium

The serosal pericardium is a closed sac within the fibrous pericardium, having a visceral and a parietal layer (**10.22**). The visceral layer, or *epicardium*, covers the heart and great vessels and is reflected into the parietal layer, which lines the internal surface of the fibrous pericardium. The reflexions of the serosal layer are arranged as two complex 'tubes', the aorta and pulmonary trunk being enclosed in one and the superior and inferior venae cavae and the four pulmonary

veins in the other. The tube surrounding the veins has the shape of an inverted J (**10.19, 32**) and the cul-de-sac within its curve is behind the left atrium and is termed the *oblique sinus*. A passage between the two pericardial 'tubes' is the *transverse sinus* (**10.19**). This has the aorta and pulmonary trunk in front and the atria and great veins behind. The arrangement of the oblique and transverse sinuses, along with that of the main 'principal' cavity, is further affected by the development of complex three-dimensional pericardial recesses between adjacent structures. (For details, illustrations and bibliography see Vesely & Cahill 1986.) These recesses can be grouped according to the siting of their orifices or 'mouths'. From the principal pericardial cavity, the *postcaval recess* projects towards the left behind the atrial termination of the superior vena cava. It is limited above by the right pulmonary artery and below by the upper right pulmonary vein. Its mouth opens superolaterally to the right. The *right* and *left pulmonary venous recesses* each project medially and upwards on the back of the left atrium between the superior and inferior pulmonary veins on each side, indenting the side walls of the oblique sinus. The *superior aortic recess* extends from the transverse sinus. From its mouth, located inferiorly, it ascends posterior to, then right of, the ascending aorta to end at the level of the sternal angle. The *inferior aortic recess*, also extending from the transverse sinus, is a diverticulum descending from a superiorly located mouth to run between the lower ascending part of the aorta and the right atrium. The *left pulmonary recess*, mouth under the fold of the left vena cava, passes to the left between the inferior aspect of the left pulmonary artery and upper border of the superior left pulmonary vein. The *right pulmonary recess* lies between the lower surface of the proximal part of the right pulmonary artery and upper border of the left atrium.

A triangular fold of serosal pericardium is reflected from the left pulmonary artery to the subjacent upper left pulmonary vein as the *fold of the left superior vena cava*. It contains a fibrous ligament, a

Right common carotid artery
Right subclavian artery
Brachiocephalic trunk
Right brachio-cephalic vein
Superior vena cava
Superior vena cava
Transverse sinus of pericardium
Right pulmonary veins
Inferior vena cava

Left internal jugular v
Left subclavian vein
Left brachiocephalic vr
Left subclavian artery
Left common carotid artery
Arch of aorta
Ligamentum arteriosum
Pulmonary trunk
Left pulmonary veins
Oblique sinus of pericardium

10.19 Interior of the serosal pericardial sac after section of the large vessels at their cardiac origin and removal of the heart (seen from the front). See text for additional named recesses of the general serosal pericardial cavity and its transverse sinus.

remnant of the obliterated *left common cardinal vein* (left duct of Cuvier, p. 302). This descends anterior to the left pulmonary hilum from the upper part of the left superior intercostal vein to the back of the left atrium, where it is continuous with the *oblique vein of the left atrium* (p. 1576). The left common cardinal vein may persist as a left superior vena cava which then replaces the oblique vein of the left atrium and empties into the coronary sinus. When both common cardinal veins persist as right and left superior venae cavae, the transverse anastomosis between them, normally forming the left brachiocephalic vein, may be small or absent. When there is a left superior vena cava, it is joined by the left superior intercostal vein.

Vessels and nerves. The arteries of the pericardium are derived from the internal thoracic and musculophrenic arteries and the descending thoracic aorta. The veins are tributaries of the azygos system. The nerve supply is from the vagus together with phrenic nerves and the sympathetic trunks.

Structure. The fibrous pericardium is compact collagenous fibrous

tissue. The serosal pericardium is a single layer of flat cells on a thin subserosal layer of connective tissue which blends with the fibrous pericardium in the parietal membrane and with the interstitial myocardial tissue in the visceral membrane. On the cardiac side, the subserosal layer contains fat, this being greatest along the ventricular side of the atrioventricular groove, the inferior cardiac border and the interventricular grooves. The main coronary vessels and their larger branches are embedded in this fat, its amount being related to the general extent of body fat and gradually increasing with age.

Pericardial puncture

Pericardial puncture can be performed either in the fifth or sixth left intercostal space lateral to the sternum sufficient to avoid the internal thoracic artery, or at the left costoxiphoid angle, passing up and backwards into the pericardial sac. The serosal pericardium extends on the pulmonary trunk, anterior to the transverse sinus, as far as the arterial ligament (p. 1504, see **10.66**).

<div align="center">HEART</div>

GENERAL INTRODUCTION

All triploblastic organisms, including chordates, overcome the limitations of diffusion over long distances by circulating a fluid from regions of high-oxygen tension and high concentration of nutrient substances to mesodermal and other cells remote from the external environment. The fluid, and its mode of circulation, vary amongst invertebrate phyla, but the majority (for example, annelid worms, arthropods and molluscs) are coelomates with closed vascular systems and some localized means of propelling 'blood' in a true circulation. The most common pattern consists of a dorsal pulsatile vessel (which may be valved and respond to muscular pacemakers under the influence of nerves), and one or more accessory structures which show varying degrees of development. Gas exchange is generally across gills and/or skin, although alternative systems (such as the tracheae of insects and lung books of spiders) occur in terrestrial groups. Echinoderms (sea urchins, starfish, etc.), the invertebrate group closest to chordates, display a unique water vascular system which takes over much of the role of the blood vascular system—a specialization which makes comparisons difficult.

Chordates possess a single heart (although accessory pulsatile vessels may be present) and the circulation is closed, but chordates differ from other coelomates in that the heart is ventral and not dorsal to the gut. In the primitive urochordates (tunicates or 'sea squirts'), the capillary beds are essentially in series, and flow of blood through the heart is bi-directional. In cephalochordates (including *Branchiostoma*, the familiar amphioxus), capillary networks are largely in parallel and blood flows through the unvalved tubular 'heart' in one direction (Randall & Davie 1980). This forms the starting point for the development of the vertebrate heart.

In tracing cardiac phylogeny, especially in deriving the mammalian heart, no direct palaeontological evidence is available. Comparison of existing arrangements in extant vertebrate groups, therefore, is the only source of information. Such comparison can be misleading. Many older textbooks, dwelling only on the degree of septation, give the impression of an orthogenetic evolution of the mammalian four-chambered heart through a series of imperfect (yet surviving) intermediates. This overlooks the fact that, in all vertebrates, the structure of the heart is intimately related to the nature of surfaces for gas exchange, to locomotion and lifestyle, and to metabolism. Hearts must function early in embryonic life, throughout development, and then in greatly changed postnatal conditions.

In its simplest form the vertebrate heart is a single pump consisting of a succession of three or four enlarged segments. These are, first, a sinus venosus draining principal veins; second, a pulsatile but thin-walled atrium; third, a thick-walled muscular ventricle; and either a so-called bulbus cordis or conus, with cardiac muscle in its wall (primitive jawless vertebrates, elasmobranchs and lungfish) or a

bulbus arteriosus (the swollen proximal end of the ventral aorta) consisting of smooth muscle and elastic tissue (teleost fish). The chambers are separated one from another by valves which maintain a unidirectional flow and permit increased pressures to develop at the arterial outlet. The conus, or bulbus arteriosus when present, opens into a ventral aorta from which arise a series of aortic arches that supply the gills before joining to form a median dorsal aorta. The heart has its own coronary circulation (except in primitive jawless vertebrates like lampreys and hagfish) and is contained in a pericardial coelom, a separated part of the general body cavity. The pericardial cavity is semi-rigid in some fish (for example, elasmobranchs) and lies dorsal to the pectoral girdle. The resultant constancy of volume aids atrial filling by suction as the ventricle empties. This effect is largely lost in tetrapods because of caudal 'migration' of the heart and less massive bony girdles. The pulsatile rhythm of vertebrate hearts is basically myogenic, but is co-ordinated with systemic demands by a supply of nerves. With increasing specialization from fishes to birds and mammals, nodes and tracts of cardiac muscle differentiate as focuses initiating contraction and as rapid conductors for the dissemination of cyclic stimuli (at particular sites the conduction is much slower, introducing physiologically imperative delays).

In most vertebrates, the cardiac tube outgrows the length of its pericardial sac, developing a sinuous bend. The venous end (sinus venosus and atrium) then becomes dorsal to the arterial end (ventricle and conus). Moreover, the heart becomes asymmetrical in position with the change from symmetrical cardinal veins to asymmetrical venae cavae. In the lungfish (Dipnoi), the venous sinus opens into the right of a partly divided atrium, a condition persisting in subsequent vertebrate classes. In frogs, most salamanders and all amniotes (reptiles, birds and mammals), this asymmetry is coupled with absorption of some of the venous sinus and its vestiges into the atrium. With complete separation of atria, a right-sided systemic venous return is established. At the arterial end, the bulbar segment of the embryo persists as the contractile bulbus cordis (conus) of the adult and, in elasmobranchs, commonly has serial valvar flaps. From these may be derived the spiral valves in the conus of lungfish and amphibians. This development is linked with the greatest era of transformation in cardiac evolution, the long series of adaptations which allowed vertebrates to spread from an aquatic to a terrestrial habitat.

It is thought that the ancestors of tetrapods were fish which were chiefly dependent on gills but could breathe air using a pharyngeal diverticulum, the so-called 'swim bladder' or, later, lungs. We have a living model for such a lifestyle in the Australian lungfish *Neoceratodus*, a facultative air-breather which relies mainly on gills and cutaneous gas exchange, but uses its lung when the oxygen concentration in the surrounding water falls (Burggren & Johansen 1986). The other two living dipnoan genera (*Protopterus* from Africa

and *Lepidosiren* from South America) are more specialized and are fully dependent on air-breathing. An inherent duality is found in the circulation of dipnoans. They have a systemic 'portal' arterial circulation (through the gills) and also a parallel pulmonary 'portal' circulation (through the walls of the lung; the same system supplying the skin and the mucous membranes of the mouth and pharynx). The adoption of air-breathing, however, creates problems for the venous return. Blood leaving the lung capillaries lacks sufficient energy to perfuse the remaining body tissues effectively and must, therefore, be returned to the heart. If it simply joins the systemic venous return, there will be large-scale mixing of oxygenated and deoxygenated blood. Division of the atrial chamber, with pulmonary venous blood returning to a separate left atrium, is, therefore, a requirement for efficient air-breathing. Such circuits already return blood to discrete atria in dipnoans and, although the ventricle is only partly divided, perfusion studies have shown that obligate air-breathers have the ability to separate the different bloodstreams— partly by virtue of the highly trabecular internal ventricular surface. The ventricular output is divided into two streams by spiral valves in a large conus arteriosus. Oxygenated blood from the left side of the heart is directed preferentially to the head and dorsal aorta while blood from the right side is directed to the 'lungs' via the more caudal gill clefts (the passage through the gills being important for the removal of carbon dioxide).

The earliest tetrapods were in existence at least 360 million years ago in the Devonian Period of the Palaeozoic. From what we now know of them, it would seem that the first tetrapods were aquatic animals using, like the lungfish *Neoceratodus*, a combination of branchial, pulmonary and cutaneous gas exchange (Coates & Clack 1991). It may be, therefore, that no sudden change, either in structure or function, occurred in the slow adaptation from aquatic to terrestrial life. There was, instead, a change of balance between several coexistent modes of respiration. These respiratory changes, inseparable from cardiac circulatory modifications, were accompanied by changes in the locomotor system, with the evolution of limbs from fins, firstly as an aid to progression within an aquatic environment but then, with changes in the girdles and spine, to fully terrestrial locomotion.

In amphibians, the gills are usually lost at metamorphosis and the branchial capillary beds disappear. Gas exchange is mainly pulmonary and buccopharyngeal, with the skin becoming an important surface for the removal of carbon dioxide. In the heart, the atria are separate chambers (although the interatrial septum is perforated in most salamanders), but the ventricle is undivided (except in the salamanders *Siren* and *Necturus*). Despite this, perfusion studies have shown that several factors (a system of ventricular trabeculae, the spiral outlet valve, the position and volume of the returning blood) enable the streams of flow to be effectively separated when the animal is breathing. When the lungs are not in use, blood returning to the right atrium from the skin and buccopharyngeal region may contain more oxygen than the blood returning to the left atrium. The absence of the ventricular septum should not, therefore, be regarded as a primitive maladaptation but as a condition which permits an important flexibility in the cardiorespiratory pattern.

The earliest amniotes completed the transition to a terrestrial lifestyle with an egg that was capable of surviving out of water and a skin that was resistant to loss of water. Although some groups have returned to an aquatic or amphibious lifestyle, respiration is almost entirely pulmonary (some turtles and sea snakes are reported to use vascularized cloacal surfaces for limited gas exchange), and is linked with a complete interatrial septum and at least partial ventricular division.

The hearts of living reptiles are varied and complex and this is not a place for a detailed review (see references for further information). Reptilian hearts are unusual in having three incompletely separated ventricular compartments and a triple or quadruple arterial cardiac outflow with a pulmonary trunk, a right and a left aorta and, in turtles, a separate brachiocephalic trunk. The two aortae join dorsally to form a single median dorsal aorta. In lizards, snakes and turtles, all the outlet vessels arise from the right side of the heart (cavum venosum), although the pulmonary trunk issues from a more ventral compartment (cavum pulmonale). Blood from the left atrium flows into a left cavum arteriosum but no outflow vessels leave this compartment. The passages between the right and left ventricles, and between the two main compartments of the right ventricle, are at least partially separated one from another by valves which open and close in response to changes in pressure such that oxygenated and deoxygenated bloodstreams remain largely separated. As in amphibians the structure of the ventricle permits substantial right-to-left shunting (approaching pulmonary bypass) within the heart when the animal stops breathing (for example, when diving or, in the case of lizards, during sustained exercise—due perhaps to the disruptive effect of repeated lateral flexions of the body). In crocodiles, the arrangement is similar to that of lizards and snakes but there are two important differences. The first is the presence of a complete interventricular septum. The second is that, while the pulmonary trunk and left aorta arise from the right ventricle as usual, the right aorta leaves the left ventricle. An opening, the foramen of Panizza, permits a shunt from the right aorta into the left during breathing when little or no blood enters from the right ventricle. As in other reptiles, the system also permits a shunt in the opposite direction when the lungs are shut down in diving. Under these conditions, blood in the right ventricle passes preferentially into the left aorta due to the higher resistance of the pulmonary circuit.

The bird heart is closely similar to that of the crocodile except that degeneration of the left aortic arch (rarely present as a remnant), suppression of the interaortic septum and loss of the connection between the right ventricle and the aortic root has resulted in a fully divided heart with no possibility of right-to-left shunting. There is also a single right aortic arch. These changes probably occurred in the small, active bipedal dinosaurs which were ancestral to the first birds. In these animals, the upright posture and terrestrial lifestyle obviated the need for right-to-left shunts and permitted the continuous breathing required for a fully active lifestyle. Despite its four chambers, the bird heart differs from that of a mammal in several respects, most notably the retention of a right rather than left aortic arch and the presence of a flap-like muscular right atrioventricular valve which lacks either papillary muscles or tendinous chords (chordae tendineae).

Bird and mammal hearts have evolved independently to permit a lifestyle in which a high level of activity is maintained by a constant high metabolic rate, with all the demands that this makes on the system in terms of requirements for oxygen and energy supply. It is orthodox to derive mammals from 'reptiles', but it should be stressed that living reptiles are as far removed from such ancestral forms as are living mammals. Consequently, as we have seen, the hearts of living reptiles are specialized, and no extant reptile can provide a model for the ancestral mammalian heart. The earliest amniotes were derived from a lineage separate from that which gave rise to living amphibians. Similarly, the ancestors of mammals were primitive amniotes which separated at a very early stage (at least 300 million years ago) from the lineage which gave rise to modern reptiles and birds. We cannot easily predict, therefore, the structure of the heart in the amniotes which were ancestral to mammals. This heart seems likely to have shown full atrial and at least partial ventricular septation. Right-to-left shunting may have remained important until the limbs were brought under the body and lateral flexion of the trunk during walking no longer disrupted ventilation. The heart of the most 'primitive' living mammals, the egg-laying monotremes, is essentially mammalian, although there is reportedly some muscle within the right atrioventricular valve and its movements are regulated directly by papillary muscles without the intervention of tendinous cords.

In all mammals, including mankind, cardiac septation is complete but during embryonic life (p. 1501) stages occur that are rather like the final arrangements in some lower vertebrates. Abnormal development can lead to congenital defects resembling conditions in those forms. The resemblance is misleading because the heart must function effectively at all but its initial stages of development. The oval foramen, a feature of mammalian prenatal development, is a necessary shunt rather than an atavistic indication of earlier incomplete atrial septation. A persistently patent oval foramen, and other such cardiac abnormalities, are due to disturbed mammalian development rather than recapitulation. Equally, the functional fetal mammalian heart, with its elegant separation of blood flows within the right atrium by a combination of small valves, pressure differences and the positions of entry of the vessels, provides clear evidence that **147**

the absence of discrete septa does not necessarily render a heart inefficient. For further details consult Embryology in this volume and the following references and their bibliographies: Foxon (1955), Johansen and Burggren (1980) and Lawson (1979).

There is no entirely logical progression in describing the heart. Whatever standpoint is used, subsequent details are presumed. The sequence adopted here is a compromise. General organization precedes external features, surface anatomy and radiology, and is then followed by internal structure, including accounts of valves, myocardium, fibrous 'skeleton', specialized conducting tissues and the cardiac cycle.

The human heart is a pair of valved muscular pumps combined in a single organ (**10.20, 24**). But, while the fibromuscular framework and conduction tissues of these pumps are structurally interwoven, each pump (the so-called 'right' and 'left' hearts) is physiologically separate, being interposed in series at different points in the double circulation. Despite this functional disposition in series, the two pumps are usually described topographically in parallel.

Of the four cardiac chambers, the two atria receive venous blood as weakly contractile reservoirs for final filling of the two ventricles, which then provide the powerful expulsive contraction forcing blood into the main arterial trunks.

The **right heart** commences at the right atrium, and receives the superior and inferior venae cavae together with the main venous inflow from the heart itself via the coronary sinus. This systemic venous blood traverses the *right atrioventricular orifice*, guarded by the *tricuspid valve*, to enter the inlet component of the right ventricle. Contraction of the ventricle, particularly its apical trabecular component, closes the tricuspid valve and, with increasing pressure, ejects the blood through the muscular right ventricular outflow tract into the pulmonary trunk and thence to the pulmonary vascular bed, which has a relatively low resistance. Changes in pressure, time relations and valvar events are described below. Many structural features of the 'right heart', including its overall geometry, myocardial architecture and the construction and the relative strengths of the tricuspid and pulmonary valves, accord with this low resistance, being associated with comparatively low changes of pressure.

The **left heart** commences at the left atrium, which receives all the pulmonary inflow of oxygenated blood and some coronary venous inflow. It contracts to fill the left ventricle through the *left atrioventricular orifice* guarded by its *mitral valve*. The valve is the entry to the inlet of the left ventricle. Ventricular contraction rapidly raises the pressure in the apical trabecular component, closing the mitral valve and opening the aortic valve so that the ventricle can eject via the left ventricular outflow tract into the aortic sinuses, ascending aorta and thence to the whole systemic arterial tree, including the coronary arteries. This vast vascular bed presents a high peripheral resistance which, with large metabolic demands, especially the sustained requirements of the cerebral tissues, explains the more massive structural organization of the 'left heart'. The ejectional phase of the left ventricle is shorter than that of the right, but its fluctuations of pressure are very much greater.

Because of its contrasting functional demands, the human heart is far from a simple pair of parallel pumps, structurally combined, even though the right and left ventricles must deliver more or less the same volume with each contraction. The heart has a complicated, spiralized, three-dimensional organization which is markedly skewed when compared with the planes of the body. Terms such as 'left' and 'right', 'anterior' and 'posterior', 'superior' and 'inferior', therefore, do not always assist the descriptions of cardiac anatomy. Another potential source of confusion is the usual study of isolated whole or dissected hearts, with the subsequent difficulty in relating details to the heart as it is positioned within the body. The following preliminary description emphasizes such difficulties so as to circumvent certain misconceptions before proceeding to an account of more detailed structure.

The principal features of cardiac anatomy can be illuminated by study of corrosion casts of normal hearts in which the two sides have been filled with resins of contrasting colours. Alternatively, similar information is obtained from horizontal mediastinal sections or scans taken at, or near, the seventh thoracic vertebral level (**10.21, 25A, B**).

The **right heart**, while forming the right aspect or 'border' (see p. 1476), follows a gentle curve and covers most of the anterior aspect of the left heart (except for a left-sided strip including the apex). Thus, the right heart forms the largest part of the **anterior** surface, its outflow tract ascending until it terminates on the **left** side of the outflow tract from the left ventricle. The sites of the tricuspid and pulmonary valves are widely separated and on different planes, the flat cavity of the right ventricle (crescentic in its section) splaying out between them. Conversely, the **left heart** (except the left-sided strip mentioned above) is largely **posterior** in position and is obscured when viewed from the front by the chambers of the right heart. The inlet to the left ventricle (containing the mitral valve) is very close to its outlet (the aortic valve), the two being embraced by the wide tract linking inlet and outlet components of the right ventricle. The

Arch of aorta
Pulmonary trunk
Superior vena cava
Right pulmonary veins
Left atrium
Right atrium
Coronary sinus
Inferior vena cava
Posterior interventricular artery
Middle cardiac vein

Arch of aorta
Superior vena cava
Pulmonary trunk
Left auricle
Right coronary artery
Right auricle
Small cardiac vein
Right ventricle
Left ventricle
Anterior descending (interventricular branch of left coronary artery, and great cardiac vein

10.20 The heart and great vessels.

Right ventricle
Cardiac apex
Left lung
Left ventricle
Left phrenic nerve
Left pleural sac
Coronary sinus
Oesophagus
Left pulmonary ligament
Descending thoracic aorta

Right atrium
Right phrenic nerve
Right pleural sac
Inferior vena cava
Right pulmonary ligament
Recess of right pleural sac
Azygos vein
Thoracic duct
Seventh thoracic vertebra

10.21 Transverse section through the mediastinum at the level of the body of the seventh thoracic vertebra, viewed from above. Note the general disposition of cardiac cavities, their intervening septa (about 45° to sagittal and coronal planes) and, orthogonal to this, the plane of the atrioventricular valves. The oesophageal plexus of nerves is clear but not labelled.

planes of the left ventricular orifices, though relatively inclined, are more nearly coplanar than those of the right. The left ventricular cavity is narrow and conical, with its tip occupying the cardiac apex. Most of the base of the heart is made up of the left atrium.

The heart is placed **obliquely** in the thorax (**10.28**). The atrial and ventricular septal structures are virtually in line but inclined forwards and to the left at about 45° to a sagittal plane. The planes of the mitral and tricuspid valves, though vertical and not precisely coplanar, are broadly at right angles to the septal plane. The right atrium, therefore, is not only to the right but also anterior and inferior to the left atrium. It is also partly anterior to the left ventricle, an important atrioventricular septum intervening. The right ventricle forms most of the anterior aspect of the ventricular mass (**10.27**), only its inferior end being to the right of the left ventricle, its upper left extremity (pulmonary orifice) being to the left and superior relative to the aortic valve. The left atrium forms most of the posterior aspect of the heart, while the left ventricle is only prominent inferiorly, running along the left margin to reach the apex. The atria are essentially right of and posterior to their respective ventricles. These general dispositions are of the greatest importance in planning or interpreting radiographs, scans, angiocardiograms and echocardiograms.

FEATURES

The heart is a hollow, fibromuscular organ of a somewhat conical or pyramidal form, with a base, apex and a series of surfaces and 'borders'. Enclosed in the pericardium (**10.19, 21, 22**), it occupies the middle mediastinum between the lungs and their pleural coverings. It is placed obliquely behind the body of the sternum and the adjoining costal cartilages and ribs (**10.25A, B, 28**). Approximately one-third of the mass lies to the right of the midline.

An average adult heart is about 12 cm from base to apex, 8–9 cm at its broadest transverse diameter and 6 cm anteroposteriorly. Its weight varies from 280–340 g (average 300 g) in males and from 230–280 g (average 250 g) in females. Cardiac weight is said to be about 0.45% of body weight in males and 0.40% in females (Hudson 1965). Adult weight is achieved between the ages of 17 and 20 years. The oblique position of the heart may be emphasized by comparing it to a rather deformed pyramid, with the base facing posteriorly and to

the right, and the apex anteriorly and to the left. A line from the apex to the approximate centre of the base, projected posterolaterally, emerges near the right midscapular line. Some surfaces of the cardiac 'pyramid' are flat, others more or less convex, these aspects merging along rather ill-defined 'borders'. Precise definition of surfaces and intervening 'borders' is, therefore, difficult. In the account which follows, official nomenclature (*Nomina Anatomica* 1989) and more generally used terms from clinical practice are given as alternatives. The heart is described as having a base and apex, its **surfaces** being designated as sternocostal (anterior); diaphragmatic (inferior); and right and left (pulmonary). Its borders are termed upper, inferior

Aorta
INF
Transverse sinus
Left atrium
Left ventricle
Oblique sinus (behind left atrium between pulmonary veins)
Myocardium
Pericardial cavity
Fibrous pericardium
Epicardium
Serosal pericardium
layer

10.22 The arrangement of the layers of the pericardium, and the location of the two sinuses within the pericardial cavity.

('acute' margin or border) and left ('obtuse' margin or border). Some name the right surface a 'border', despite its extent. One avoidable source of confusion is the use of 'posterior', which can be replaced with the unambiguous term 'diaphragmatic'. If posterior is to be used for a cardiac surface, it should be reserved for the base. But, compounding this difficulty, there are a number of different usages of the term 'cardiac base' (see below).

GROOVES ON THE CARDIAC SURFACES

The division of the heart into four chambers produces boundaries visible externally as grooves or sulci. Some are deep and obvious and contain prominent structures. Others are less distinct, even barely perceptible, and are sometimes obscured, in part, by the major structures crossing them. The *coronary*, or *atrioventricular*, *groove* (or *sulcus*) separates the atria from the ventricles. This groove, containing the main trunks of the coronary arteries, is oblique. It descends to the right on the sternocostal surface (10.27), separating the right atrium (and its auricular appendage) from the oblique right margin of the right ventricle and its infundibulum. Its upper left part is obliterated where it is crossed by the pulmonary trunk and, behind this, the aorta from which originate the coronary arteries. Continuing to the left, the groove curves around the 'obtuse margin' and descends to the right, separating the atrial base from the diaphragmatic surface of the ventricles (10.32). This diaphragmatic part of the coronary groove then curves around the 'acute margin' at its lower right end to become confluent with the sternocostal part. Thus, the groove passes from high on the left to low on the right, with the diaphragmatic part being a little to the left of the sternocostal. A section which includes the coronary groove is at about 45° to the sagittal plane and at a greater but variable angle to the transverse and coronal planes. It approximately traverses the lines of attachment of the atrioventricular valves and (even less precisely) those of the aortic and pulmonary valves. A line at right angles to the centre of this plane will descend forwards and leftwards to the cardiac apex.

Internally, the ventricles are separated by the septum (pp. 1480, 1483), the mural margins of which correspond to the anterior and inferior (diaphragmatic) interventricular grooves. The anterior groove, seen on the sternocostal cardiac surface, is near and almost parallel to the left ventricular obtuse margin. On the diaphragmatic surface, in contrast, the groove is closer to the midpoint of the ventricular mass. The interventricular grooves extend from the coronary groove to the apical notch on the acute margin. This is a little to the right of the true cardiac apex.

CARDIAC BASE, APEX, SURFACES, BORDERS

Posterior aspect of the heart. The true *cardiac base*, this is somewhat quadrilateral, with curved lateral extensions. It faces back and to the right, separated from the thoracic vertebrae (fifth to eighth in the recumbent, sixth to ninth in the erect posture) by the pericardium, right pulmonary veins, oesophagus and aorta. It is formed mainly by the left atrium, and only partly by the posterior part of the right atrium (10.32). It extends superiorly to the bifurcation of the pulmonary trunk and inferiorly to the posterior part of the atrioventricular groove containing the coronary sinus and branches of the coronary arteries (p. 1477). It is limited to the right and left by the rounded surfaces of the corresponding atria. These are separated by the shallow *interatrial groove*. The point of junction of the atrioventricular, interatrial and posterior interventricular grooves is termed the *crux of the heart* (10.32). Two pulmonary veins on each side open into the left atrial part of the base, while the superior and the inferior vena cava open into the upper and lower parts of the right atrial basal region. The area of the left atrium between the openings of right and left pulmonary veins forms the anterior wall of the oblique pericardial sinus (10.19). This description of the anatomical base reflects the usual position of the heart in the thorax. Some confusion is produced by other current usages of the term 'base'. It is often applied to the segment of the atrioventricular and ventriculo-arterial junctions seen after dissections through the coronary groove (10.31). This area is better termed the base of the ventricles. In clinical practice, auscultation in or near the parasternal parts of the second intercostal spaces is often described as occurring at the *clinical 'base'*, to make the contrast with the *clinical 'apex'*.

Such descriptions, while less than perfect anatomically, will almost certainly persist.

Anatomical apex of the heart. This is the apex of the conical left ventricle, which is directed down, forwards and to the left. The left lung and pleura overlap it. It is located most commonly behind the fifth left intercostal space, near or a little medial to the midclavicular line.

Anterior, sternocostal surface of the heart (10.26, 27). Facing forwards and upwards, this has an acute right and a more gradual left convexity. It consists of an atrial area above and to the right, and a ventricular part below and to the left of the atrioventricular groove. The atrial area is occupied almost entirely by the right atrium. The left atrium is largely hidden by the ascending aorta and pulmonary trunk. Only a small part of the left appendage projects forwards to the left of the pulmonary trunk. Of the ventricular region, about one-third is made up by the left and two-thirds by the right ventricle. The site of the septum between them is indicated by the anterior interventricular groove. The sternocostal surface is separated by the pericardium from the body of the sternum, the sternocostal muscles and the third to the sixth costal cartilages. Owing to the bulge of the heart to the left, more of this surface is behind the left costal cartilages than behind the right ones. It is also covered by the pleural membranes and by the thin, anterior edges of the lungs, except for a triangular area at the cardiac incisure of the left lung. The lungs and their pleural coverings are variable in their degree of overlap of the heart.

Inferior, diaphragmatic surface of the heart (10.32). Largely horizontal, it slopes down and forwards a little towards the apex. It is formed by the ventricles (chiefly the left) and rests mainly upon the central tendon but also, apically, on a small area of the left muscular part of the diaphragm. It is separated from the anatomic base by the atrioventricular groove and is traversed obliquely by the posterior interventricular groove.

Left surface of the heart. Facing up, back and to the left, this consists almost entirely of the obtuse margin of the left ventricle, but has a small part of the left atrium and its auricle contributing superiorly. Convex and widest above, and crossed here by the atrioventricular groove, it narrows to the cardiac apex. It is separated by the pericardium from the left phrenic nerve and its accompanying vessels, and by the left pleura from the deep concavity of the left lung.

Right surface of the heart. A rounded surface is formed by the right atrial wall and is separated from the mediastinal aspect of the right lung by the pericardium and the pleural coverings. Its convexity merges below into the short intrathoracic part of the inferior vena cava and above into the superior vena cava. The *terminal groove* (*sulcus terminalis*) is a prominent landmark between the true atrial and the venous components of the right atrium, curving approximately along the junction of the sternocostal and right surfaces (10.29).

Upper border of the heart. This is atrial (mainly the left atrium). Anterior to it are the ascending aorta and the pulmonary trunk (10.19). At its extremity the superior vena cava enters the right atrium.

Right border of the heart. Corresponding to the right atrium, its profile is slightly convex to the right and it approaches the vertical.

Inferior border of the heart. Also known as the *acute margin* of the heart, it is sharp, thin and nearly horizontal. It extends from the lower limit of the right border to the apex and it is formed mainly by the right ventricle, with a small contribution from the left ventricle near the apex.

Left border of the heart. Also known as the *obtuse margin*, it separates the sternocostal and left surfaces. It is round and mainly formed by the left ventricle but, to a slight extent superiorly, is formed by the auricle of the left atrium. It descends obliquely, convex to the left, from the auricle to the cardiac apex.

The right and left chambers of the heart will be described in sequence

in terms of their general form, their walls and their internal features. The two sides have much in common, such as the structure of valvar leaflets, tendinous cords, and papillary muscles of atrioventricular (inlet) valves, and the architecture of the cusps of the pulmonary and aortic (outlet) valves. Repetition, as far as possible, will be kept to a minimum.

RIGHT ATRIUM

General and external features

The *interatrial septum* (or *atrial septum*) is oblique, so the right atrium is anterior as well as to the right of the left atrium (10.27, 32), also extending inferior to it. Its walls form the right upper sternocostal surface, the convex right (pulmonary surface) and a little of the right side of the anatomic base. The superior vena cava opens into its dome and the inferior vena cava into its lower posterior part (10.27). An extensive muscular pouch, the *auricle* or appendage, projects anteriorly to overlap the right side of the ascending aorta. The auricle is a broad, triangular structure and has a wide junction with the true atrial component of the atrium (10.23A, 29). The junction between the venous part (*sinus venarum*) and the atrium proper is marked externally by a shallow groove, the *sulcus terminalis*, extending between the right sides of the openings of the two venae cavae. The sulcus terminalis corresponds, internally, to the terminal crest (*crista terminalis*) which is the site of origin of the extensive pectinate muscles arising serially at right angles from the crest (10.33). Posteriorly, the vertical interatrial groove descends to the crux.

Anteriorly, the right atrium is related to the anterior part of the mediastinal surface of the right lung, separated from it by pleura and pericardium. Laterally, the atrium is also related to the mediastinal surface of the right lung, but anterior to its hilum and separated from it by the pleura, right phrenic nerve and pericardiacophrenic vessels and pericardium. Posteriorly and to the left (10.32, 35), the atrial septum and the surrounding infolded atrial walls separate the right from the left atrium (the mural infolding being indicated by the extensive interatrial groove). Posteriorly and to the right are the right pulmonary veins. Medially are the ascending aorta and, to a lesser extent, the root of the pulmonary trunk and its bifurcation.

Interior surface of the right atrium (10.24, 34). The interior surface can be divided into three regions: a smooth-walled venous component, posteriorly, leading, anteriorly, to the vestibule of the tricuspid valve and the auricle. The wall of the vestibule is smooth, but its junction with the auricle is ridged all around the atrioventricular junction. The smooth-walled part receives the opening of the venae cavae and the coronary sinus. It represents

the venous component ('sinus venosus') of the developing heart (p. 303). The wall of the vestibule has a ridged surface and that of the auricle is trabeculated; both are derived from the embryonic atrium proper.

Opening into the venous component are the *superior vena cava* returning blood from head, neck and upper limb through an orifice which faces infero-anteriorly and has no valve, and the *inferior vena cava*. The latter vessel is larger than its superior counterpart and returns blood from the lower part of the body into the lowest part of the atrium near the septum. Anterior to its orifice is a flap-like valve, the *Eustachian valve* or valve of the inferior vena cava (10.33). Of varying size, this valve is found along the lateral, or right, margin of the vein. When traced inferiorly, it runs into the sinus septum (see below) where it is contiguous with the valve of the coronary sinus (*Thebesius' valve*, also known as the *Thebesian valve*). The lateral part of the Eustachian valve becomes continuous with the lower end of the terminal crest. The valve is a fold of endocardium enclosing a few muscular fibres. It is large during fetal life, when it serves to direct richly oxygenated blood from the placenta through the oval foramen of the atrial septum into the left atrium. The valve varies markedly in size in postnatal life, sometimes being cribriform or filamentous but often being absent. A particularly prominent recess is seen postero-inferiorly relative to the orifice of the coronary sinus (see below). This is the *postEustachian sinus*.

Also opening into the venous atrial component is the coronary sinus. This vessel returns the majority of blood from the heart itself, opening between the orifice of the inferior vena cava, the oval fossa and the vestibule of the atrioventricular opening (10.33). The coronary sinus is often guarded by a thin, semicircular valve which covers the lower part of the orifice (Thebesius' valve). The upper limb of this valve joins with the Eustachian valve and, from this commissure, a tendinous structure runs into the sinus septum (the septum between the coronary sinus and the oval fossa). The tendinous structure, called the *tendon of Todaro*, runs forwards to insert into the central fibrous body. It is one of the landmarks of the triangle of Koch (10.36 see below).

The orifice of the coronary sinus forms a prominent landmark in the right atrium (10.33). The sinus itself, however, lies within the left atrioventricular groove (10.32). It is the conduit for return of most of the venous blood from the heart, although some atrial veins drain directly to the right or left atrial chambers. The coronary sinus commences at the point where the oblique vein of the left atrium joins. The sinus receives the middle and small cardiac veins close to its junction with the right atrium.

Multiple small venous orifices, draining the minimal atrial veins, are found scattered around the atrial walls. They return a small
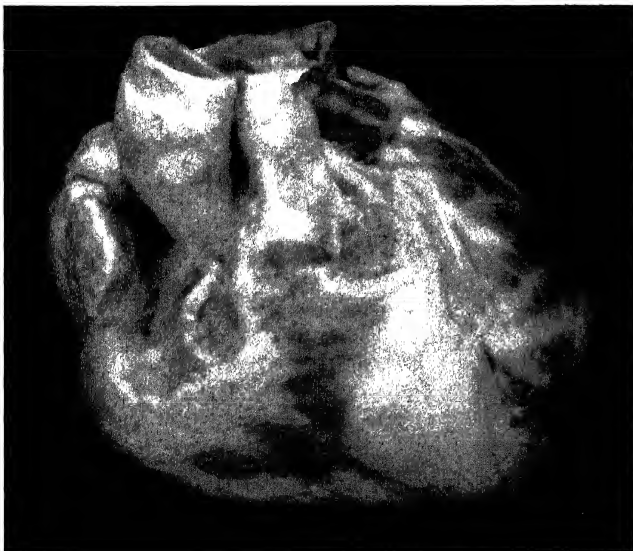
10.23A. The anterior surface of the removed heart oriented so that it lies, as far as possible, in its position within the body.
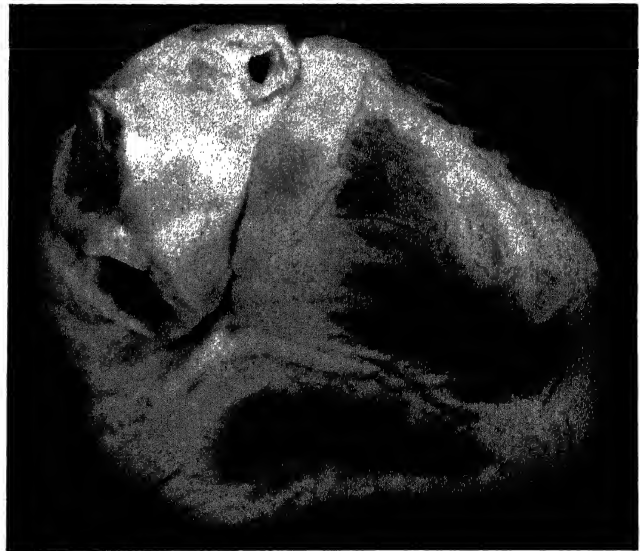
B. The posterior surface of the removed heart, oriented to take its position within the body.

10.24 This dissection shows the crucial relation between subaortic outflow tract and ventricular inlet components, as shown in **10.25**. The non-coronary sinus of the aorta, with its corresponding aortic valvar cusp, has been removed.

fraction of blood from the heart (p. 1575), being most numerous on the septal aspect. The anterior cardiac veins and, sometimes, the right marginal vein may enter the atrium through larger orifices (p. 1576).

The atrium proper and the auricle are separated from the venous sinus by the *terminal crest (crista terminalis)*. This smooth, muscular ridge begins on the upper part of the septal surface and, passing anterior to the orifice of the superior vena cava, skirts its right margin to reach the right side of the orifice of the inferior vena cava (**10.33**). It marks the site of the right venous valve of the embryonic heart (p. 303), and corresponds externally to the terminal groove

(p. 1477). Within the superior part of the groove, lateral to, and extending below, the orifice of the superior vena cava, is found the sinus node (p. 1496).

The *pectinate muscles (musculi pectinati)*, almost parallel muscular ridges, extend anterolaterally from the terminal crest and reach into the auricle, where they form multiple trabeculations.

The septal wall presents the *oval fossa (fossa ovalis)*, an oval depression found above and to the left of the orifice of the inferior vena cava. Its floor is the *primary atrial septum, the 'septum primum'* (p. 303). The rim of the fossa is prominent and, although often said to represent the edge of the so-called *'septum secundum'* (p. 304), in

A

B
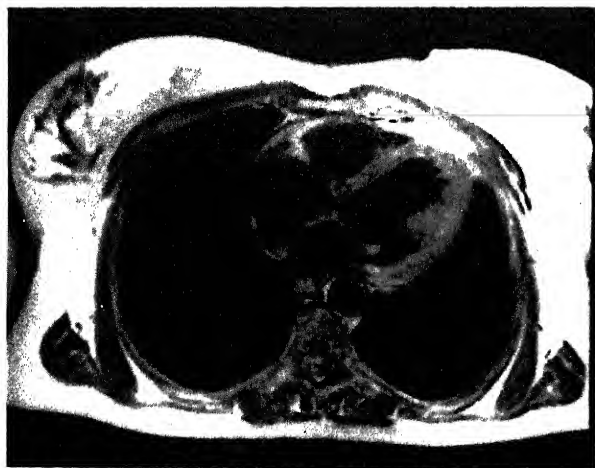
10.25 Computed tomograms of the thorax. A. Through the body of the seventh thoracic vertebra. B. Through the intervertebral disc between the seventh and eighth vertebrae. Note the overall disposition of the heart, its apex, base, oblique, interatrial and interventricular septa and, orthogonal to this, of the atrioventricular valves. Note also the atrioventricular septum, papillary muscles, trabeculae carneae, descending thoracic aorta and contrasting areas of right and left lungs and pleurae. (Provided by Shaun Gallagher, Guy's Hospital; photography by Sarah Smith.)
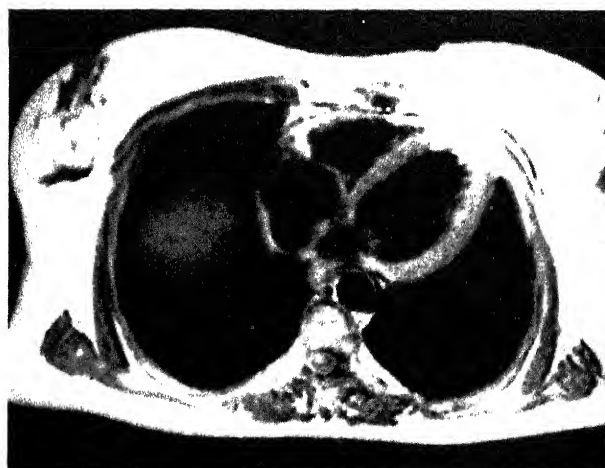
Common carotid arteries   Internal jugular vein

Internal jugular vein
Vagus nerve
Inferior thyroid vein
Phrenic nerve
Internal thoracic artery
Superior vena cava
Fibrous pericardium
Serosal pericardium
Ascending aorta
Right atrium
Horizontal fissure of lung
Diaphragm
Central tendon

Jugular lymph trunk
Subclavian vein
Subclavian artery
Left superior intercostal vein
Vagus nerve
Phrenic nerve
Pulmonary trunk
Right ventricle
Cardiac apex beneath pericardium

10.26   Dissection which displays the heart, the great vessels and the lungs in situ. The sternum and the sternal ends of the costal cartilages, together with the parietal pleura on each side, have been excised and the mediastinal pleura and parietal layer of the pericardium over the sternocostal surface of the heart have been removed. The lungs have been displaced to expose the heart and the epicardium dissected off the heart and roots of the great vessels. On the right side, the inferior cardiac branch of the vagus nerve descends between the brachiocephalic artery and the right brachiocephalic vein. On the left side, a communication descends from the left superior intercostal vein and crosses the aortic arch and the left pulmonary artery to become continuous with the oblique vein of the left atrium.

reality it is merely the infolded walls of the atrial chambers. It is most distinct above and in front of the fossa, usually being deficient inferiorly. A small slit is sometimes found at the upper margin of the fossa, ascending beneath the rim to communicate with the left atrium. This represents failure of obliteration of the fetal oval foramen, which remains patent in up to one-third of all normal hearts.

Antero-inferior in the right atrium is the large, oval vestibule leading to the orifice of the tricuspid valve. A triangular zone (the *triangle of Koch*, 10.36) is found between the attachment of the septal leaflet of the tricuspid valve, the anteromedial margin of the orifice of the coronary sinus, and the round, collagenous, palpable, sub-endocardial tendon of Todaro. The triangle is a landmark of particular surgical import, indicating the site of the atrioventricular node and its atrial connections (p. 1499). Anterosuperior to the insertion of the *tendon of Todaro*, the septal wall is the **atrioventricular** component of the *membranous septum*, intervening between the right atrium and subaortic outlet of the left ventricle (10.36). The atrial

Superior vena cava
Ascending aorta
Right auricle
Hook displacing right auricle
Right atrium
Right coronary artery in coronary sulcus
Small cardiac vein
Inferior vena cava

Left atrium
Pulmonary trunk
Left auricle
Infundibulum
Anterior interventricular branch of left coronary artery
Great cardiac vein
Left ventricle 'obtuse' margin
Right ventricle
Apex
Right ventricle 'acute' margin

10.27   The anterior or sternocostal surface of the heart.
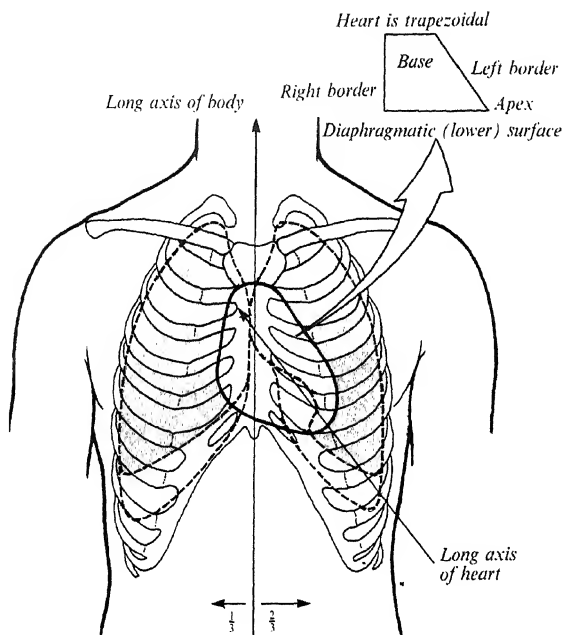
10.28 The front of the thorax, showing the surface relations of the bones, lungs (purple), pleurae (blue) and heart (red outline). Compare **10.46** for further cardiac detail.
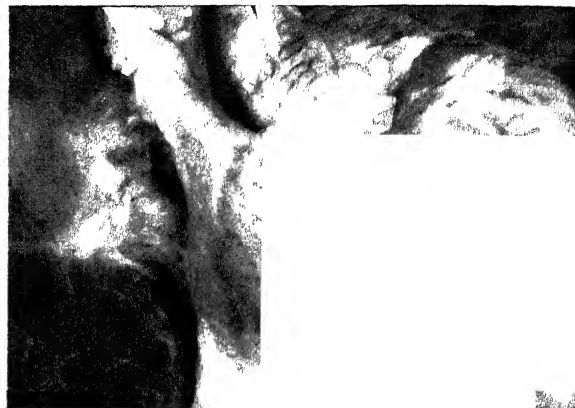
10.29 Removal of the pericardium shows the right margin of the heart, made up mostly of the right atrium. Note the characteristic terminal groove (sulcus terminalis).

wall bulges anterosuperiorly above the membranous septum. This area is the aortic mound (*torus aorticus*) and marks the location of the non-coronary sinus of the aorta with its enclosed valvar cusp (p. 1488).

RIGHT VENTRICLE

The right ventricle extends from the right atrioventricular (tricuspid) orifice nearly to the cardiac apex. It then ascends to the left to become the *infundibulum*, or *conus arteriosus*, reaching the pulmonary orifice and supporting the cusps of the pulmonary valve. Topographically, the ventricle possesses: an inlet component, supporting and surrounding the tricuspid valve; a coarsely trabeculated apical component; and the muscular outlet or infundibulum surrounding the attachments of the cusps of the pulmonary valve (**10.37A**).

External features

The convex *anterosuperior surface* makes up a large part of the sternocostal aspect of the heart (**10.23A**), separated from the thoracic wall only by the pericardium. The left pleura and, to a lesser extent, the anterior margin of the left lung are interposed above and to the left. The *inferior surface* is flat and is related mainly, with the interposition of the pericardium, to the central tendon and a small adjoining muscular part of the diaphragm. The *left* and *posterior wall* is the ventricular septum. This is slightly curved and bulges into the right ventricle so that, in sections across the cardiac axis, the outline of the right ventricle is crescentic (**10.38**). A delicate collagenous band, the tendon of the infundibulum (conus ligament), is held by some to connect the pulmonary muscular infundibulum posteriorly to the root of the aorta. The wall of the right ventricle is significantly thinner (3–5 mm on average) than that of the left, the ratio usually being about 1 to 3.

Internal features

1480   The inlet and outlet components of the ventricle, supporting and

surrounding the leaflets of the tricuspid and pulmonary valves respectively, are separated in the roof of the ventricle (**10.31**) by the prominent *supraventricular crest* (*crista supraventricularis*). The crest is a thick, muscular, highly arched structure, extending obliquely forwards and to the right from a *septal limb* high on the interventricular septal wall to a *mural* or *parietal limb* on the anterolateral right ventricular wall. The posterolateral aspect of the crest provides a principal attachment for the anterosuperior leaflet of the tricuspid valve (see below). The crest's septal limb may be continuous with, or embraced by, the septal limbs of the septomarginal trabecula (see below). The inlet and outlet regions extend apically into and from the prominent coarsely trabeculated component of the ventricle. The inlet component is itself also trabeculated, whereas the outlet component (or infundibulum) has predominantly smooth walls. The trabeculated appearance is due to myriad irregular muscular ridges and protrusions, which are known collectively as *trabeculae carnae*, and are lined by endocardium. These protrusions and intervening grooves impart great variation in wall thickness. Protrusions vary in extent from mere ridges to trabeculae which are fixed at both ends but free in-between. Other conspicuous protrusions are the papillary muscles, which are inserted at one end onto the ventricular wall and are continuous at the other end with collagenous cords, the chordae tendineae, inserted on the free edge and elsewhere on the free aspect of the atrioventricular valves (p. 1481). One protrusion in the right ventricle, the *septomarginal trabecula* or septal band, is particularly prominent. It reinforces the septal surface where, at the base, it divides into limbs which embrace the supraventricular crest. Towards the apex, it supports the anterior papillary muscle of the tricuspid valve and, from this point, crosses to the parietal wall of the ventricle as the 'moderator band' (this alternative name records an old idea that the septomarginal trabecula prevents overdistension of the ventricle). A further series of prominent trabeculae extend from its anterior surface and run onto the parietal ventricular wall. These are the septoparietal trabeculations (**10.37A**). The smooth-walled *outflow tract*, or *infundibulum* (*conus arteriosus*), ascends to the left

above the septoparietal trabeculations and **below** the arch of the supraventricular crest to the pulmonary orifice.

TRICUSPID VALVE

The atrioventricular valvar complex, in both right and left ventricles, comprises the following:

- the orifice and its associated annulus
- the leaflets
- the supporting *tendinous cords* (*chordae tendineae*) of various types
- the papillary muscles.

Harmonious interplay of all these, together with the atrial and ventricular myocardial masses (p. 1494), depends on the conduction tissues (p. 1495) along with the mechanical cohesion provided by the fibro-elastic cardiac skeleton. All parts change substantially in position, shape, angulation and dimensions during a single cardiac cycle.

Tricuspid valvar orifice

The largest valvar orifice (circumference of around 11.4 cm in males and 10.8 cm in females according to Silver et al 1971), it is best seen from its atrial aspect (10.31). It has a clear line of transition from the atrial wall or septum to the lines of attachment of the valvar leaflets. Its margins are not precisely in a single plane; at a near approximation it is almost vertical but at about 45° to the sagittal plane and slightly inclined to the vertical, such that it 'faces' (on its ventricular aspect) anterolaterally to the left and somewhat inferiorly (10.46). Roughly triangular, its margins are described as antero-superior, inferior and septal, corresponding to the lines of attachment of the valvar leaflets.

The *annulus* of the tricuspid valve is an ill-defined term used without uniformity. Elementary accounts often describe all four valvar orifices as surrounded by uniform rings of collagenous tissue, the rings interconnected by dense masses of collagen which, in the mitral and tricuspid valves, are situated precisely at the atrioventricular junctions (presumed also to separate the atrial and ventricular myocardial masses). Only some of these assumptions are true. The connective tissues around the orifice of the atrioventricular valves, while serving to separate atrial and ventricular myocardial masses completely except at the point of penetration of the atrioventricular bundle, vary in density and disposition around the valvar circumference. Extending from the right fibrous trigone component of the central fibrous body are a pair of curved, tapered, subendocardial tendons, or 'prongs' (*fila coronaria*) which partly encircle the circumference; the latter is completed by more tenuous, deformable fibroblastic sulcar areolar tissue. The extent of fibrous tissue also varies with sex and age (Walmsley & Watson 1978). Nevertheless, the tissue within the atrioventricular junction around the tricuspid orifice is less robust than similar elements found at the attachments of the mitral valve (p. 1485). Furthermore, in the tricuspid valve, the topographical 'attachment' of the free valvar leaflets does not wholly correspond to the internal level of attachment of the fibrous core of the valve to the junctional atrioventricular connective tissue. It is the line of attachment of the leaflet which is best appreciated in the heart when examined grossly, and this feature is also more readily discerned clinically.

Tricuspid valve leaflets

It is usually possible to distinguish three leaflets in the tricuspid valve, hence the name. They are located septally, antero-superiorly and inferiorly, corresponding to the marginal sectors of the atrioventricular orifice so named. Each is a reduplication of endocardium enclosing a collagenous core, continuous marginally and on its ventricular aspect with diverging fascicles of tendinous cords (see below) and basally confluent with the annular connective tissue. All leaflets of the atrioventricular valves display, passing from the free margin to the inserted margin, *rough, clear* and *basal zones*. The rough zone is relatively thick, opaque and uneven on its ventricular aspect where most tendinous cords are attached. The atrial aspect of the rough zone makes contact with the comparable surface of the adjacent leaflets during full closure of the valve. The clear zone is smooth and translucent, receives few tendinous cords and has a thinner fibrous core. The basal zone, extending about 2–3 mm from

the circumferential attachment of the leaflets, is thicker, contains more connective tissue and is vascularized and innervated, containing the insertions of the atrial myocardium.

The *anterosuperior leaflet* is the largest component of the tricuspid valve (10.37B). It is attached chiefly to the atrioventricular junction on the posterolateral aspect of the supraventricular crest, but extends along its septal limb to the membranous septum, ending at the *anteroseptal commissure*. One or more notches often indent its free margin. The attachment of the *septal leaflet* passes from the *inferoseptal commissure* on the posterior ventricular wall across the muscular septum and then angles across the membranous septum to the anteroseptal commissure. The *inferior leaflet* is wholly mural in attachment and guards the diaphragmatic surface of the atrioventricular junction; its limits are the inferoseptal and *antero-inferior commissures*.

Tendinous cords (chordae tendineae)

The tendinous cords are fibrous collagenous structures supporting the leaflets of the atrioventricular valves. *False chordae* connecting papillary muscles to each other or to the ventricular wall including the septum, or passing directly between points on the wall (and/or septum), are irregular in numbers and dimensions in the right ventricle. The true chordae usually arise from small projections on the tips or margins of the apical thirds of papillary muscles, but sometimes from the bases of papillary muscles or directly from the ventricular walls and the septum. They are attached to various parts of the ventricular aspects or the free margins of the leaflets. They were classified by Tandler (1913) into first, second and third order chordae according to the distance of the attachment from the margins of the leaflets. Subsequent authors have usually followed this classification, although the scheme has little functional or morphological merit. According to their morphology, nonetheless, it is possible to distinguish several patterns (Lam et al 1970; Silver et al 1971).

Fan-shaped chordae have a short stem from which branches radiate to attach to the margins (or the ventricular aspect) of the zones of apposition between leaflets and to the ends of adjacent leaflets (10.37A, B). *Rough zone chordae* arise from a single stem which usually splits into three components which attach to the free margin, the ventricular aspect of the rough zone and to some intermediate point on the leaflet, respectively. *Free edge chordae* are single, threadlike and often long, passing from either the apex or the base of a papillary muscle into a marginal attachment, usually near the midpoint of a leaflet or one of its scallops. *Deep chordae*, also long, pass beyond the margins and, branching to various extents, reach the more peripheral rough zone or even the clear zone. *Basal chordae* are round chordae or flat ribbons, long and slender or short and muscular. They arise from the smooth or trabeculated ventricular wall and attach to the basal component of a leaflet.

Papillary muscles

The two major papillary muscles in the right ventricle are located in anterior and posterior positions; a third, smaller muscle has a medial position along with several smaller, and variable, muscles attached to the ventricular septum. The *anterior papillary muscle* is largest. Its base arises from the right anterolateral ventricular wall below the antero-inferior commissure of the inferior leaflet and it also blends with the right end of the septomarginal trabecula. The *posterior*, or *inferior*, *papillary muscle* arises from the myocardium below the inferoseptal commissure. It is frequently bifid or trifid. The *septal*, or *medial*, *papillary muscle* is small but typical, and arises from the posterior septal limb of the septomarginal trabecula. All the major papillary muscles supply chordae to **adjacent** components of the leaflets they support. A feature of the right ventricle, however, is that the septal leaflet is tethered by individual tendinous chordae directly to the ventricular septum. Such septal insertions are never seen in the left ventricle. When closed, the three leaflets fit snugly together, the pattern of the zones of apposition confirming the trifoliate arrangement of the tricuspid valve.

PULMONARY VALVE

The pulmonary valve, guarding the outflow from the right ventricle,   148

surmounts the infundibulum and is situated at some distance from the other three cardiac valves (**10.51, 52**). Its general plane faces superiorly to the left and slightly posteriorly. It has three *semilunar leaflets* or *cusps* attached by convex edges partly to the infundibular wall of the right ventricle and partly to the commencement of the pulmonary trunk; the line of attachments is curved, rising at the periphery of each cusp near their zones of apposition (the *commissures*) and reaching the sinutubular ridge of the pulmonary trunk (**10.43A**). Removal of the cusps shows that the fibrous semilunar attachments enclose three crescents of infundibular musculature within the pulmonary sinuses, while three roughly triangular segments of arterial wall are incorporated within the ventricular outflow tract beneath the apex of each commissural attachment (**10.43A**). There is, thus, no proper circular 'annulus' supporting the leaflets of the valve, the *fibrous semilunar attachment* being an essential requisite for snug closure of the nodules and lunules of the cusps (see below) during ventricular diastole. It is difficult precisely to name the cusps and corresponding sinuses of the pulmonary valve and trunk according to the co-ordinates of the body since the valvar orifice is obliquely positioned. The official nomenclature (*Nomina Anatomica* 1989) refers to an *anterior*, a *posterior* and a *septal* cusp, based on their position in the fetus. The position changes with development and in the adult there are two *anterior* cusps, *right* and *left*, and a *posterior* one.

Each cusp is a fold of endocardium, with an intervening, and variably developed, fibrous core. The core is substantial along both the free edge and the semilunar attached border, and the latter is particularly thickened at the deepest central part (nadir) of the base of each cusp (thus never forming a simple complete fibrous ring). Central in the free margin of each cusp is a localized thickening of collagen, the *nodule of Arantius*. Perforations within the cusps close to the free margin and near the commissures are frequently present but of no functional significance. Each semilunar cusp is contained within one of the three sinuses of the pulmonary trunk. Except for differences in relations of timing and pressures, opening and closure of the pulmonary valve has much in common with that of the aortic valve (see p. 1487, **10.55**).

LEFT ATRIUM

Though smaller in volume than the right, the *left atrium* has thicker walls (3 mm on average). Its cavity and walls are largely formed by the proximal parts of the pulmonary veins, incorporated into the atrium during development (p. 303). The only clear derivative of the left part of the embryonic atrium is the auricle, along with the vestibule of the mitral valve. The left atrium is roughly cuboidal and extends behind the right atrium, separated from it by the obliquely positioned septum (**10.25A, B**). Thus, the right atrium is in front and anterolateral to the right part of the left atrium. The left part is concealed anteriorly by the initial segments of the pulmonary trunk and aorta, with part of the transverse pericardial sinus between it and these arterial trunks. Antero-inferiorly, and to the left, it adjoins the base of the left ventricle at the orifice of the mitral valve (see below). Its posterior aspect forms most of the anatomical base of the heart and is approximately quadrangular, receiving the terminations of (usually) two pulmonary veins from each lung. It forms the anterior wall of the oblique pericardial sinus (**10.19**). This surface ends at the shallow vertical interatrial groove that descends to the cardiac crux. The left atrial auricle is constricted at its atrial junction and all the pectinate muscles of the left atrium are contained within it. It is characteristically longer, narrower and more hooked than the right auricle, its margins being more deeply indented. It turns forwards to the left of the pulmonary trunk, overlapping its origin (**10.30, 39**).

Interiorly, the four *pulmonary veins* open into the upper posterolateral surfaces of the left atrium, two on each side. Their orifices are smooth and oval, the left pair frequently opening via a common channel. The *left atrioventricular orifice* is fully described below. Some minimal cardiac veins return blood directly from the myocardium to the cavity of the left atrium. The left atrial aspect of the septum has a characteristically rough appearance, bounded by a crescentic ridge, concave upwards, which marks the site of the oval foramen (p. 304).

LEFT VENTRICLE

General and external features

The left ventricle is constructed in accordance with its role as a powerful pump needed to sustain pulsatile flow in the high-pressured systemic arteries. Variously described as half-ellipsoid or cone-shaped, it is longer and narrower than the right ventricle, extending from its base in the plane of the coronary groove to the cardiac apex. Its long axis descends forwards and to the left. In transverse section, at right angles to the axis, its cavity is oval or nearly circular, with walls about three times thicker (8–12 mm) than those of the right ventricle. It forms part of the sternocostal, left and inferior (diaphragmatic) cardiac surfaces. Except where obscured by the aorta and pulmonary trunk, the base of the ventricular cone is superficially separated from the left atrium and atrial auricle by part of the atrioventricular groove, the coronary sinus running in the posterior aspect of the groove to reach the right atrium (**10.30, 32**). The anterior and posterior interventricular grooves indicate the lines of mural attachment of the ventricular septum and the limits of the left and right ventricular territories. The sternocostal surface of the ventricle curves bluntly into its left surface at the obtuse margin.

Internal features

Like the right, the left ventricle has an inlet region, guarded by the mitral valve (*ostium venosum*), an outlet region, guarded by the aortic valve (*ostium arteriosum*), and an apical trabecular component

10.30 The characteristic morphology of the left atrial appendage (compare with **10.29**, the right appendage from the same heart).

(40A, B, C). The left atrioventricular orifice, with its mitral valve, admits atrial blood during diastole, flow being towards the cardiac apex. After closure of the mitral leaflets, and throughout the ejection phase of systole, blood is expelled from the apex through the aortic orifice. In contrast to the orifices within the right ventricle, those of the left ventricle are in close contact, with fibrous continuity between the leaflets of the aortic and mitral valves (the subaortic curtain; 10.42). The inlet and outlet turn sharply round this fibrous curtain (10.40c, 51).

The anterolateral wall is the concavo-convex *ventricular septum*, a muscular wall whose convexity is the posteromedial profile of the right ventricle as seen in section. It thus completes the circular outline of the left ventricle. Towards the aortic orifice, the septum becomes the thin, collagenous interventricular component of the *membranous septum*, an oval or round area below and confluent with the fibrous triangle separating the right and the non-coronary cusps of the aortic valve (p. 1488).

Between the lower limits of the free margins of the leaflets of the mitral valve and the apex of the ventricle, the muscular walls are deeply trabeculated. These *trabeculae carneae* are finer and more intricate than those of the right ventricle, but similar in structure (p. 1480, 10.40A, B). Trabeculation is characteristically well developed near the apex, whereas the upper reaches of the septal surface are smooth (10.42).

MITRAL VALVE

The general comments already made in respect to the tricuspid valve apply equally to the mitral. As expected, therefore, the valve has an orifice with its supporting annulus, leaflets, a variety of tendinous chordae and papillary muscles.

10.31 This section of the heart ·is taken to either side of the oblique atrioventricular groove, but is then laid horizontal and photographed from the atrial aspect. It shows the interrelationships of the four cardiac valves at the so-called base of the heart. Note the central location of the aorta.
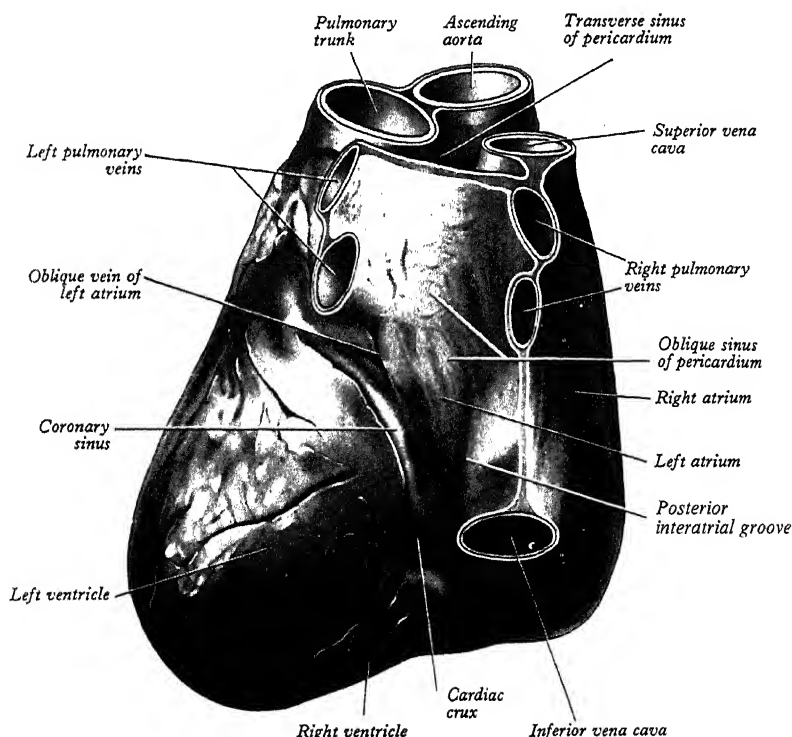
10.32 The base and the diaphragmatic surface of the heart. The serosal pericardium is in situ and its cut edge is seen around the great vessels; its disposition is highly schematic (recesses omitted). See text for additional details. The cardiac crux results from the confluence of the posterior interatrial groove, the posterior atrioventricular groove and the posterior interventricular groove.

Ascending aorta

Pulmonary trunk

Superior vena
cava

Right
auricle

Crista terminalis

Limbus fossae
ovalis

Fossa ovalis

Torus aorticus

Orifice of coronary
sinus

Valve of coronary
sinus

Musculi pectinati

Septal leaflet of
tricuspid valve

Valve of inferior
vena cava

Inferior vena cava
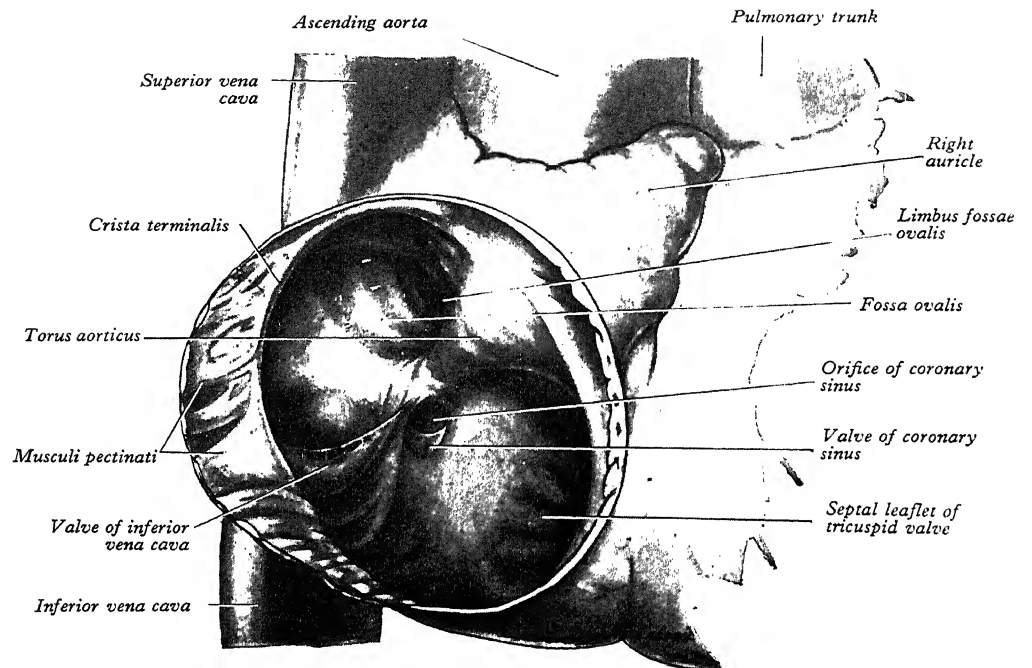
10.33   The interior of the right atrium, viewed from the front.

Pulmonary
trunk

Ascending
aorta

Left auricle

Right auricle

Left anterior cusp
of pulmonary valve

Infundibulum

Supra-
ventricular
crest

Anterior leaflet
of tricuspid
valve

Anterolateral
papillary
muscle of left
ventricle

Anterior papillary
muscle of
right ventricle

Moderator band

Posteromedial
muscle of left
ventricle
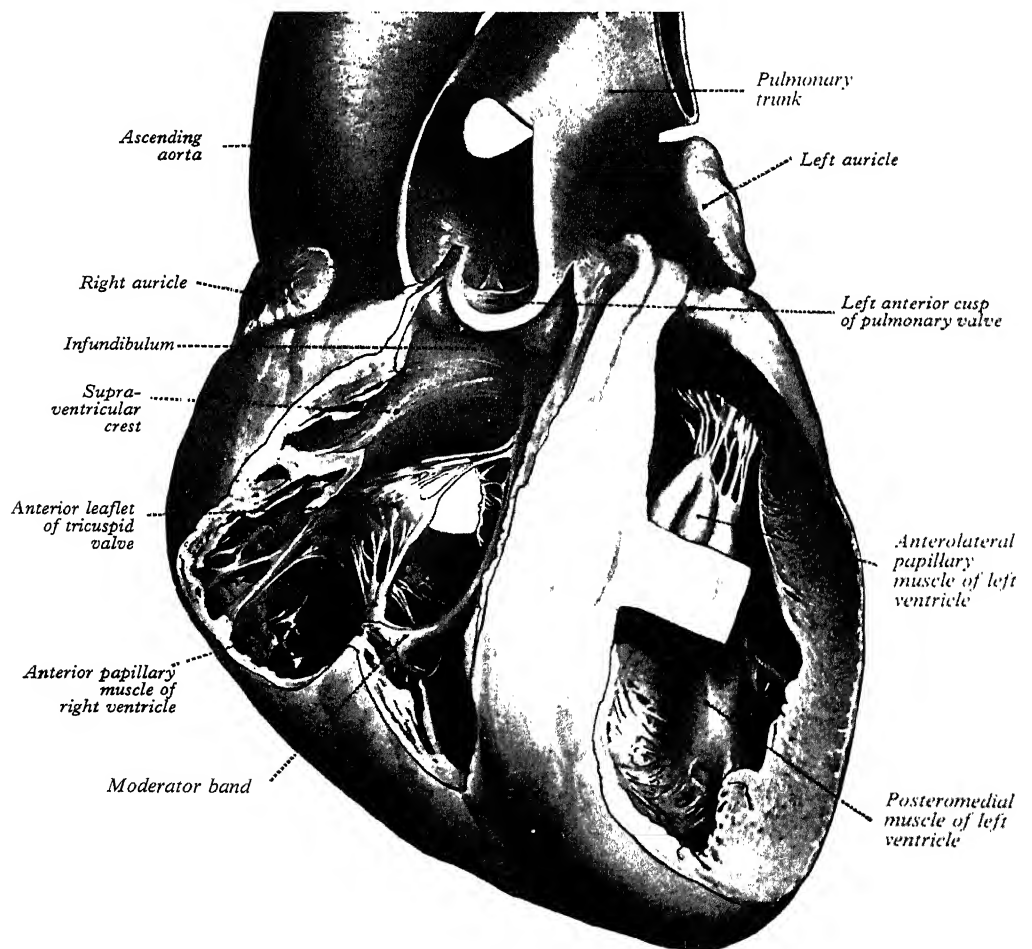
10.34   A dissection opening the ventricles, viewed from the front.

10.35 The surfaces of the right atrium are separated by the deep interatrial groove (Waterston's groove) from the left atrium. This groove forms the anterosuperior margin of the atrial septum (the oval fossa). Note the solitary line of coaptation of the leaflets of the mitral valve.

Mitral orifice

The mitral orifice is a well-defined transitional zone between the atrial wall and the bases of the leaflets (**10.40a**). It is smaller than the tricuspid orifice (mean circumference: 9.0 cm in males, 7.2 cm in females, according to Ranganathan et al 1970). The approximately circular orifice is almost vertical in diastole and at 45° to the sagittal plane but with a slight forward tilt. Its ventricular aspect faces anterolaterally to the left and a little inferiorly towards the left

ventricular apex. It is almost coplanar with the tricuspid orifice but posterosuperior to it, whereas it is postero-inferior and slightly to the left of the aortic orifice. The mitral, tricuspid and aortic orifices are intimately connected centrally at the *central fibrous body* (p. 1493). When the leaflets of the mitral valve close, they form a single zone of coaptation, termed by some the *commissure* (**10.35**).

The *annulus* of the valve is not a simple fibrous ring, but comprises fibrocollagenous elements of varying consistency from which the fibrous core of the leaflets take origin. These variations allow major changes in the shape and dimensions of the annulus at different stages of the cardiac cycle and ensure optimal efficiency in valvar action.

The annulus is strongest at the internal aspects of the left and right fibrous trigones (**10.51**). Extending from these structures, the anterior and posterior coronary prongs (tapering, fibrous, sub-endocardial tendons) partly encircle the orifice at the atrioventricular junction (**10.51, 52**). Between the tips of the prongs, the atrial and ventricular myocardial masses are separated by a more tenuous sheet of deformable fibro-elastic connective tissue. Spanning anteriorly between the trigones, the fibrous core of the central part of the anterior aortic leaflet of the mitral valve is a continuation of the fibrous *subaortic curtain* which descends from the adjacent halves of the left and non-coronary cusps of the aortic valve (**10.42**).

Mitral valvar leaflets

Since the earliest descriptions, these leaflets have been described as paired structures. Hence, the name 'bicuspid valve' is more explicit, though erroneous (the leaflets are not cuspid, or peaked, in form) and surely less picturesque than the clinical term 'mitral'. Confusion, controversy and difficulties in quantitation have arisen, however, because small accessory leaflets are almost always found between
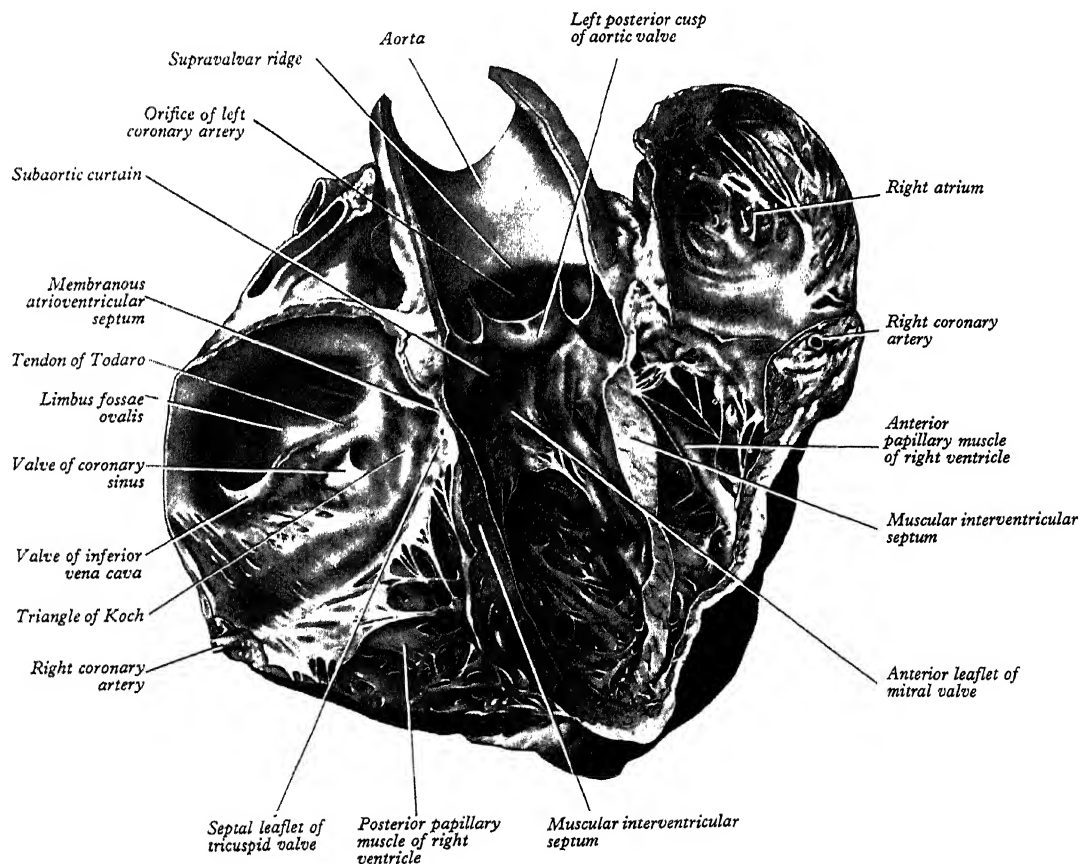
10.36 The interior of the heart revealed by incising it along its right and lower surfaces and excising the pulmonary trunk and infundibulum. The rest of the front of the heart has been turned over to the left.
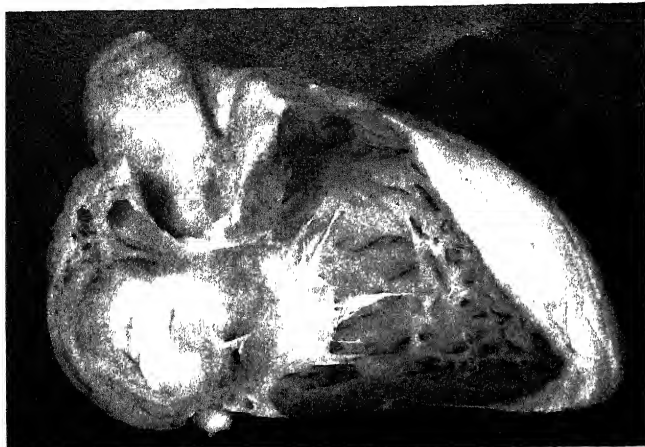
10.37A. Removal of the sternocostal parietal surface of the heart shows the components of the right ventricle. Note the supraventricular crest separating the attachments of the tricuspid and pulmonary valves.

the two major leaflets. These problems can be resolved if the mitral valve is described as consisting 'of a continuous veil attached around the entire circumference of the mitral orifice' (Harken et al 1952). Its free edge bears several indentations, two being sufficiently deep and regular to be nominated as the ends of a solitary and oblique zone of apposition, or *commissure* (10.31, 35). It is more usual, nonetheless, for these anteromedial and posterolateral extremities themselves to be designated as two commissures, each positionally named as indicated. The official names for these leaflets, anterior and posterior, though simple, are somewhat misleading because of the obliquity of the valve.

When the valve is laid open (10.40B), its *anterior leaflet* (aortic, septal, 'greater' or anteromedial) is seen to guard one-third of the circumference of the orifice and to be semicircular or triangular, with few or no marginal indentations. Its fibrous core (*lamina fibrosa*) is continuous on the outflow aspect, beyond the margins of the fibrous subaortic curtain, with the right and left fibrous trigones (10.31, 36, 43B, 51). Between these, it is continuous with the fibrous curtain itself and, beyond the trigones, with the roots of the annular fibrous prongs (10.52). The leaflet has a deep crescentic rough zone receiving various tendinous chordae (see below). The ridge limiting the outer margin of the rough zone indicates the maximal extent of

10.38 Transverse section through the ventricles of the isolated heart, viewed from below. Note that in this illustration the heart is not positioned as it would be in situ: in the latter position the crescentic 'right' ventricle overlaps most of the anterior surface of the 'left' ventricle.
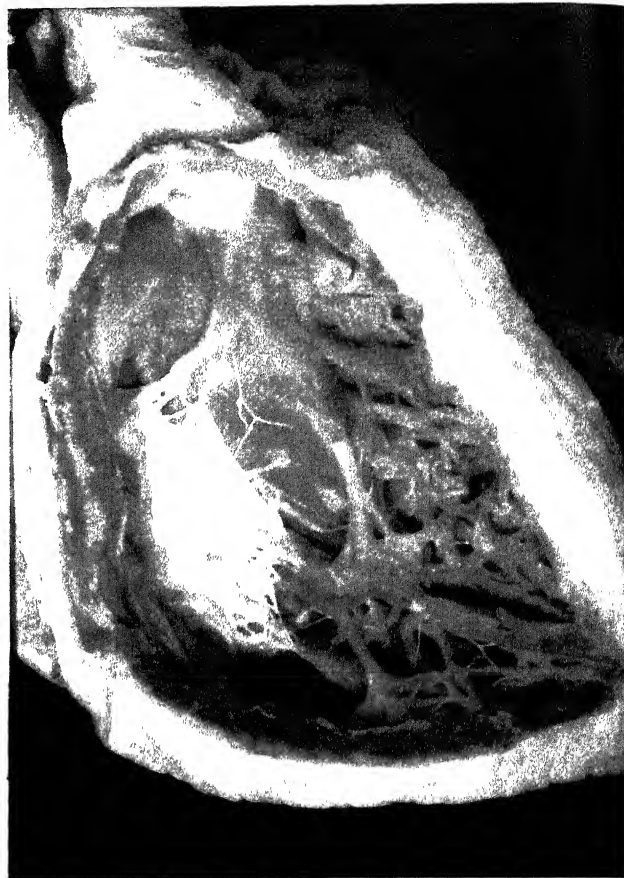
10.37B. This anterior view through a window into the right ventricle shows the extent of the supraventricular crest. Note the relatively smooth-walled infundibulum, the prominent spetomarginal trabecule and the extensive septoparietal trabeculation.

surface contact with the mural leaflet in full closure. A clear zone is seen between the rough zone and the valvar annulus which is devoid of attachments of chordae, though its fibrous core carries extensions from chordae attached in the rough zone. The anterior leaflet has no basal zone, continuing instead into the valvar curtain. Hinging on its annular attachment, and continuous with the subaortic curtain, it is critically placed between the inlet and the outlet of the ventricle. During passive ventricular filling and atrial systole, its smooth atrial surface is important in directing a smooth flow of blood towards the body and apex of the ventricle. After the onset of ventricular systole and closure of the mitral valve, the ventricular aspect of its clear zone merges into the smooth surface of the subaortic curtain which, with the remaining fibrous walls of the subvalvar aortic vestibule, forms the smooth boundaries of the ventricular outlet.

The *posterior leaflet* (mural, ventricular, 'smaller' or posterolateral) has usually two or more minor indentations. Lack of definition of major intervalvar commissures has previously led to disagreement and confusion concerning the territorial extent of this leaflet and the possible existence of accessory scallops. Examination of the valve in closed position, however, shows that the posterior leaflet can conveniently be regarded as all the valvar tissue posterior to the anterolateral and posteromedial ends of the major zone of apposition with the aortic leaflet. Thus defined, it has a wider attachment to the annulus than does the anterior leaflet, guarding two-thirds of the circumferential attachments. There are further indentations usually dividing the mural leaflet into a relatively large middle 'scallop' and smaller anterolateral and posteromedial commissural 'scallops'. Each scallop has a crescentic, opaque rough zone, receiving the attachment of the chords on its ventricular aspect which define the area of valvar apposition in full closure. From the rough zone to within 2–3 mm of its annular attachment is a membranous clear zone devoid of
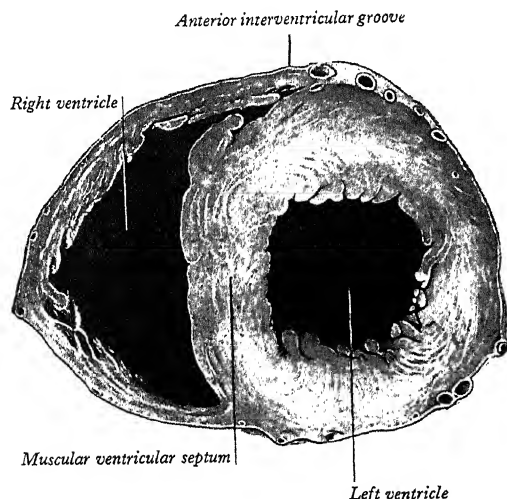
Orifice of upper left pulmonary vein

Ascending aorta

Interior of left auricle

Superior vena cava

Cut edge of serous pericardium

Chordae tendineae

Right pulmonary veins

Anterior papillary muscle

Interatrial septum

Trabeculae carneae

Mitral valve, anterior leaflet

Posterior papillary muscle

Inferior vena cava
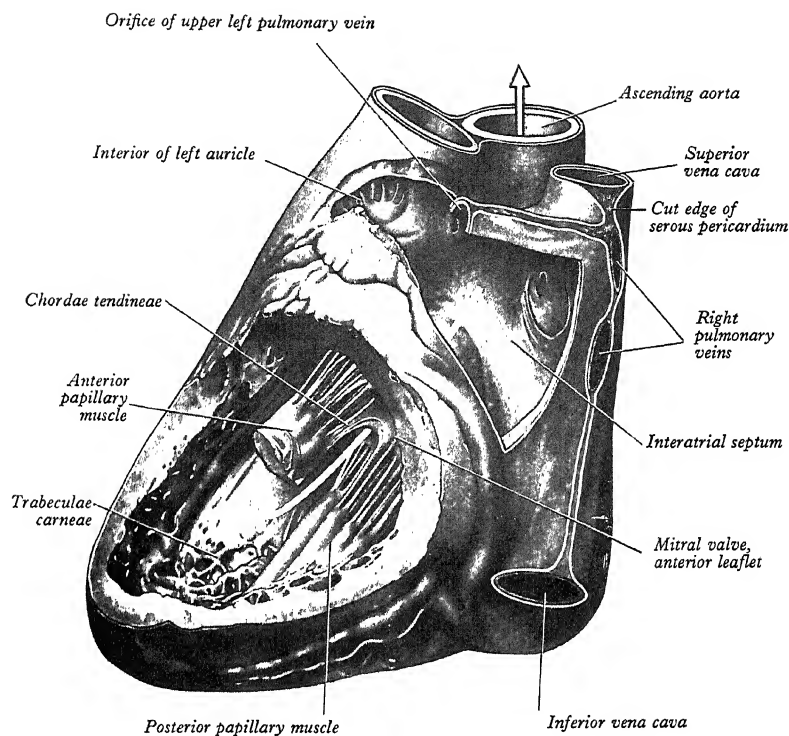
10.39 Dissection showing the interior of the left side of the heart. The white arrow indicates the course of blood flow from the left atrium through the left ventricle to the aorta.

chordae. The basal 2 3 mm is thick and vascular, and receives basal chordae. The ratio of rough to clear zone in the anterior leaflet is about 0.6. In the middle 'scallop' of the posterior leaflet, it is 1.4. Thus, much more of the mural leaflet is in apposition with the aortic leaflet during closure of the mitral valve.

Mitral chordae tendineae (tendinous cords)

These cords resemble those supporting the tricuspid valve (**10.40A**, B). False chordae (trabeculae carneae **10.39, 40A, B**), are also irregularly distributed as in the right ventricle. They occur in about half of all human left ventricles and often cross the subaortic outflow. Many contain extensions from the ventricular conduction tissues. Such left ventricular bands can often be identified by cross-sectional echocardiography. Their role, if any, has still to be determined. True chordae of the mitral valve may be divided into interleaflet (or commissural) chordae, rough zone chordae, including the special strut chordae, so-called 'cleft' chordae, and basal chordae. Most true chordae divide into branches from a single stem soon after their origin from the apical third of a papillary muscle, or proceed as single chordae dividing into multiple branches near their attachment. Basal chordae, in contrast, are solitary structures passing from the ventricular wall to the mural leaflet.

There is such marked variation between the arrangement of the chordae in individual normal hearts that any detailed classification loses much of its clinical significance. Suffice it to say that, in the majority of hearts, the chordae support the entire free edges of the valvar leaflets together with varying degrees of their ventricular aspects and bases. There is some evidence to suggest that those valves with unsupported areas of the free edge become prone to prolapse in later life.

Papillary muscles

The two muscles supporting the leaflets of the mitral valve also vary in length and breadth and may be bifid. The *anterolateral muscle* arises from the sternocostal mural myocardium, the *posteromedial* from the diaphragmatic region. Tendinous chordae arise mostly from the tip and apical third of each muscle, but sometimes take origin near their base. The chordae from each papillary muscle diverge and

are attached to corresponding areas of closure on **both** valvar leaflets (**10.40B**).

Opening of the mitral valve

At the onset of diastole, opening is passive but rapid, the leaflets parting and projecting into the ventricle as left atrial pressure exceeds left ventricular diastolic pressure. Passive ventricular filling proceeds as atrial blood pours to the apex, directed by the pendant aortic leaflet of the valve. The leaflets begin to float passively together, hinging on their annular attachments, partially to occlude the ventricular inlet. Atrial systole now occurs, jetting blood apically and causing re-opening of the leaflets. As maximal filling is achieved, the leaflets again float rapidly together. Closure is followed by ventricular systole, which starts in the papillary muscles and continues rapidly as general contraction of the walls and septum. Co-ordinated contraction of the papillary muscles raises the tension in the chordae and promotes joining of the corresponding points on opposing leaflets, preventing their eversion. With general mural and septal excitation and contraction, left ventricular pressure rapidly rises (**10.55**). The leaflets 'balloon' towards the atrial cavity and the atrial aspects of the rough zones come into maximal contact. Precise papillary contraction, and increasing tension in the chordae, continues to prevent valvar eversion and maintains valvar competence.

The orifices and the leaflets of both atrioventricular valves undergo considerable changes in position, form and area during a cardiac cycle (**10.50**). Both valves move anteriorly and to the left during systole, and reverse their motion in diastole. The mitral valve reduces its orificial (annular) area by as much as 40% in systole. Its shape also changes from circular to crescentic at the height of systole, the annular attachment of its aortic leaflet being the concavity of the crescent. The attachment of its mural leaflet, although remaining convex, contracts towards the anterior wall of the heart.

AORTIC VALVE

The smooth left ventricular outflow tract, or aortic vestibule, ends at the leaflets of the aortic valve. Although stronger in construction, the aortic valve resembles the pulmonary (**10.42, 43, 44, 45**) in

10.40A This dissection shows the papillary muscles of the left ventricle in their natural position. The cords from each muscle diverge to support the leaflets.
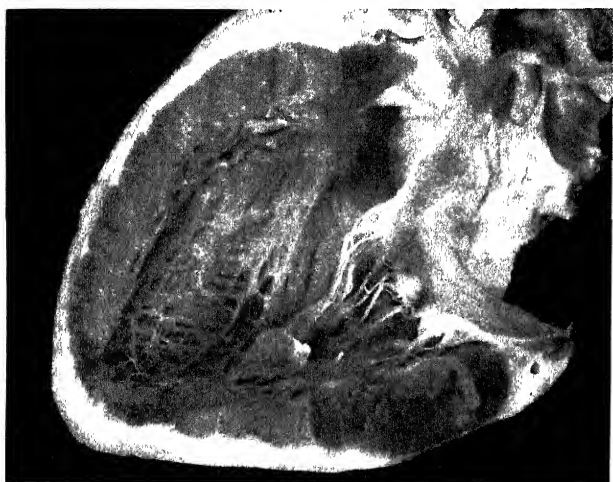
10.40B The left ventricle has been dissected by removing the obtuse margin so as to reveal its inlet, apical trabecular and outlet components.
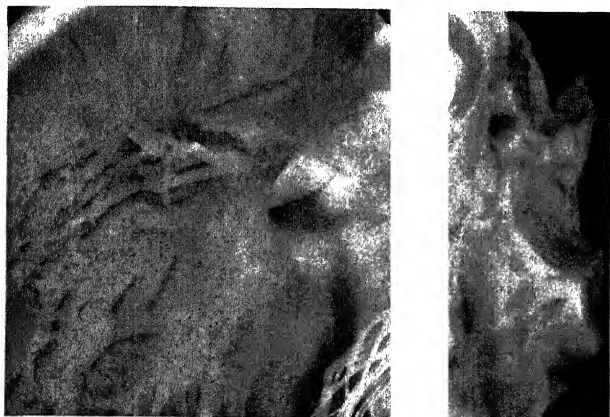
10.40C This detail of the heart shown in B emphasizes the area of fibrous continuity between the leaflets of the aortic and mitral valves.

possessing three semilunar leaflets, the *cusps*, supported within the three aortic sinuses of Valsalva. Although the aortic valve, like the pulmonary valve, is often described as possessing an annulus in continuity with the fibrous skeleton, there is no complete collagenous ring supporting the attachments of the leaflets. Instead, again as with the pulmonary valve, the anatomy of the aortic valve is dominated by the fibrous semilunar attachment of the cusps (**10.43B**).

Cusps

The cusps are, in part, attached to the aortic wall and in part to the supporting ventricular structures. The situation is more complicated than in the pulmonary valve, because parts of the cusps also take origin from the fibrous subaortic curtain, being continuous with the aortic leaflet of the mitral valve (**10.42**). This area of continuity is thickened at its two ends to form the right and left fibrous trigones (**10.51**). But, again as with the pulmonary valve (**10.43B**), the semilunar attachments incorporate segments of ventricular tissue within the base of each aortic sinus. These sinuses and leaflets are conveniently named as being *right, left* and *non-coronary* according to the origins of the coronary arteries (**10.43B**). The semilunar attachments also incorporate three triangular areas of aortic wall within the apex of the left ventricular outflow tract. Since these triangular areas are part of the aortic wall rather than the left ventricle, interposing between the bulbous aortic sinuses, they separate the cavity of the left ventricle from the pericardial space. Removal of the triangles in an otherwise intact heart is instructive in demonstrating the relationships of the aortic valve, which can justly be considered as the keystone of the heart. The base of the triangle between the non-coronary and the left coronary cusps is continuous inferiorly with the fibrous aortic-mitral curtain. The apex of this triangle 'points' into the transverse pericardial space. The triangle between right and non-coronary cusps has, as its base, the membranous components of the interventricular septum and thus 'faces' the right ventricle, whereas its apex 'points' towards the transverse pericardial space behind the origin of the right coronary artery. The third triangle, between the two coronary cusps, has its base on the muscular ventricular septum. Its apex 'points' to the plane of space found between the aortic wall and the free standing sleeve of right ventricular infundibular musculature which supports the cusps of the pulmonary valve. Although the basal attachments of each leaflet are thickened and collagenous at their ventricular origins, there is no continuous collagenous skeleton supporting, in circular fashion, all the attachments of the cusps of the aortic valve. Valvar function depends primarily upon the semilunar attachments of the cusps.

The cusps themselves are folds of endocardium with a central fibrous core. With the valve half-open, each equals slightly more than a quarter of a sphere, an approximate hemisphere being completed by the corresponding sinus. Each cusp has a thick basal border, deeply concave on its aortic aspect, and a horizontal free margin. The latter is only slightly thickened except at its midpoint where it has an aggregation of fibrous tissue, the valvar *nodule of Arantius*. Flanking each nodule, the fibrous core is tenuous, forming the *lunules* of translucent and occasionally fenestrated valvar tissue (**10.42**). Such fenestrations are of no functional significance. The aortic surface of each cusp is rougher than its ventricular aspect.

Three sets of names currently exist for the aortic cusps. Official terms in the *Nomina Anatomica* (1989) refer to presumed fetal positions before full cardiac rotation has occurred. They are *posterior, right* and *left*. Corresponding terms based on the approximate positions in maturity are *anterior, left posterior* and *right posterior*. But, as already indicated, widespread clinical terminology links both cusps and sinuses to the origins of the coronary arteries. Thus, the anterior is the *right coronary* structure, left posterior is *left coronary*, and right posterior is *non-coronary*. These clinical terms are preferable since they are simple and unambiguous.

Aortic sinuses (of Valsalva)

The aortic sinuses are more prominent than those in the pulmonary trunk. The upper limit of each sinus reaches considerably beyond the level of the free border of the cusp and forms a well-defined complete circumferential *sinutubular ridge* when viewed from the aortic aspect (**10.43B**). Coronary arteries usually open near this ridge within the upper part of the sinus, but are markedly variable in their origin. The walls of the sinuses are largely collagenous near the

attachment of the cusps, but the amount of lamellated elastic tissue increases with distance from the zone of attachment. Strands of myocardium may enter this fibro-elastic wall. At the midlevel of each sinus, its wall is about half the thickness of the supravalvar aortic wall and less than one-quarter of the thickness of the sinu-tubular ridge. At this level, the mean luminal diameter of the beginning of the aortic root is almost double that of the ascending aorta. All such details are functionally significant in the mechanism of valvar motion.

The mechanism of valvar motion

During diastole, the closed aortic valve supports an aortic column of blood at high but slowly diminishing pressure. Each sinus and its cusp form a hemispherical chamber. The three nodules are apposed and the margins and lunular parts of adjacent cusps are tightly apposed on their ventricular aspects. From the aortic aspect, the closed valve is tri-radiate, three pairs of closely compressed lunules radiating from their nodules to their peripheral commissural attachments at the sinutubular junction (10.41, 45). As ventricular systolic pressure rises, it exceeds aortic pressure and the valve is passively opened. The fibrous wall of the sinuses nearest the aortic vestibule is almost inextensible but, in the upper parts of sinuses, the wall is fibro-elastic. Under left ventricular ejection pressure, the radius here increases about 16% in systole. Hence the commissures move apart, making the orifice triangular when fully open. The free margins of the cusps then become almost straight lines between peripheral attachments. But they do not flatten against the sinus walls, even at maximal systolic pressure, which is probably an important factor in subsequent closure. During ejection, most blood enters the ascending aorta, but some enters the sinuses, forming vortices which help to maintain the triangular 'midposition' of the cusp during ventricular systole and probably initiate their approximation with the end of systole. Tight and full closure ensues with the rapid drop of ventricular pressure in diastole.

Commissures narrow, nodules aggregate and the valve reassumes its triradiate form. Experiments indicate that about 4% of ejected blood regurgitates through a valve with normal sinuses, while 23% regurgitates through a valve without them. The normal structure of the aortic sinuses also promotes non-turbulent flow into the coronary arteries.

Similar events occur in the pulmonary valve, albeit more leisurely, the pressure profiles being less extreme (10.55) and the valvar structure less substantial.

SURFACE ANATOMY OF THE HEART

The surface projections to be described below apply to an average

Pulmonary valve — *Right auricle*

Left auricle — *Aortic valve*

Left pulmonary veins — *Superior vena cava*

Right pulmonary veins

Line of cut serous pericardium — *Left atrium*
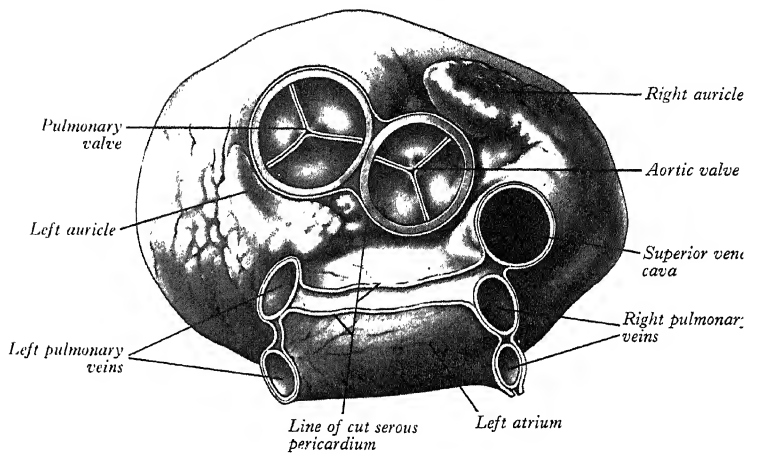
10.41 The heart viewed from above. The two continuous white lines which enclose the pulmonary trunk and aorta on the one hand and the pulmonary veins and the superior vena cava on the other, indicate the continuation of the parietal layer of the serous pericardium with the serous epicardium. The floor of the transverse sinus is seen from above, with the left coronary artery running in it. This diagram, from an earlier edition, has been retained for its pericardial details. However, in some respects it is misleading: the aortic and pulmonary valves are not, as shown, coplanar; the pulmonary valve is distinctly higher than the aortic valve; furthermore the planes of the valves 'face' approximately at right angles to each other.

adult. They are considerably modified by age, sex, stature and proportions, respiration and posture. The projections of the position of the valves to the surface are not the best sites for their auscultation (10.46). The cardiac apex almost corresponds to the apex beat, which is usually visible and always palpable in the fifth intercostal space, slightly medial to midclavicular line, about 9 cm from midline in average adult males. The apex beat is the most inferolateral point at which a pulsation can be felt. The true cardiac apex, however, is a short distance further inferolaterally. It does not contact the thoracic wall in systole.

The cardiac sternocostal surface, projected to the anterior thoracic wall, is a trapezoid (10.29, 46). Its right border corresponds to a line from the superior border of the right third costal cartilage, about 1 cm from the sternal margin, to the sixth costal cartilage. The line is convex to the right and is maximally distant from the midline (about 3–4 cm) in the fourth intercostal space. It represents the

Left coronary orifice — *Nodule on left posterior cusp*

Subaortic curtain (Intervalvar septum) — *Right coronary orifice*

Mitral valve anterior leaflet — *Lunule on anterior cusp*

Membranous part of ventricular septum

Right ventricle

Muscular part of ventricular septum

Chordae tendineae
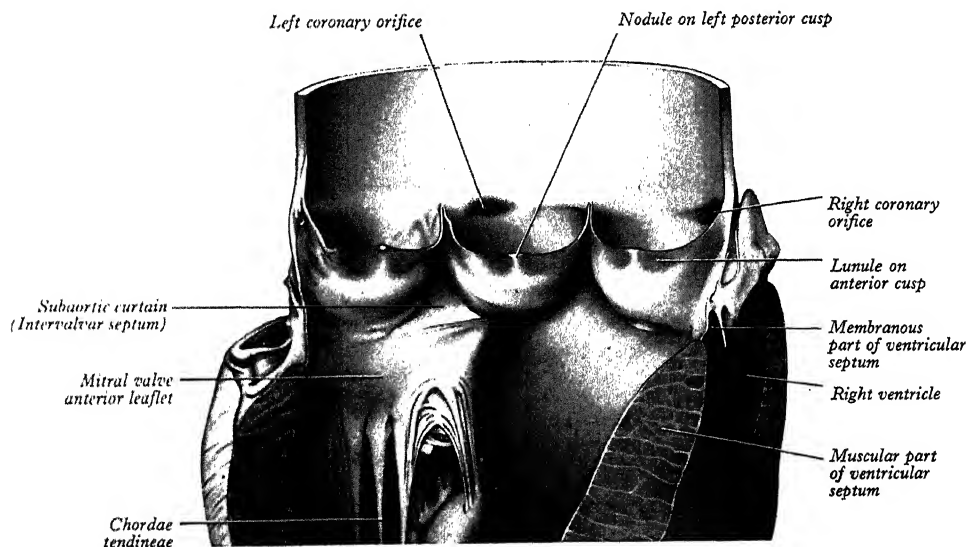
10.42 The aortic orifice opened from the front to show the cusps of the aortic valve, their nodules, lunules, commissures and the triple-scalloped line of annular attachment. Also shown is the continuity of the subaortic

curtain with the mitral anterior leaflet (i.e. 'aortic baffle') and the coronary orifices.
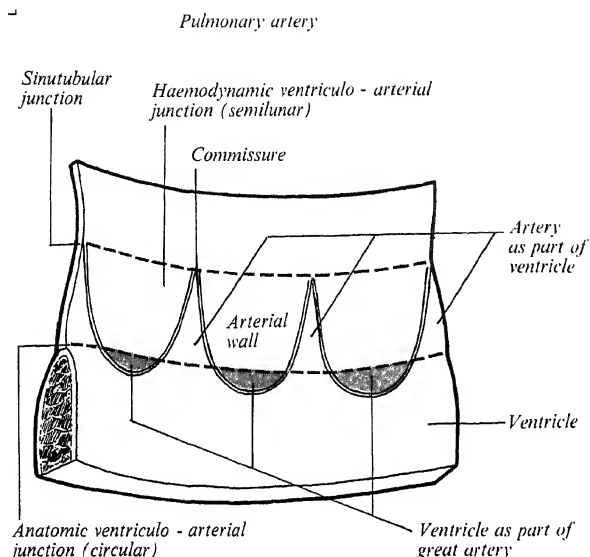
10.43A. In this diagram of the aortic root (compare with B the cusps have been resected at the attachment to the aortic wall. Note the relation of the cusp insertions and the ventriculo-arterial junction.
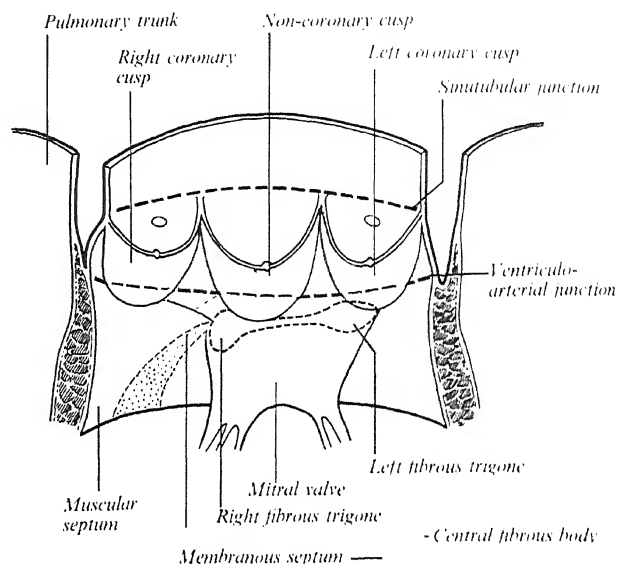
10.43B. The root of the aorta cut open and distended, to show the insertion of the semilunar cusps. The diagram illustrates the structure of the zone of fibrous continuity between the cusps of the aortic valve and the leaflets of the mitral valve and their relation with the fibrous trigones. It also shows the semilunar attachment of the leaflets (compare with 10.43A)
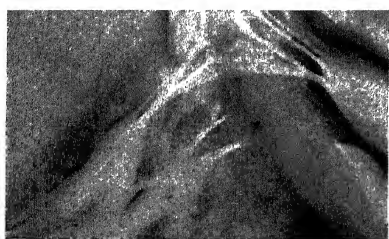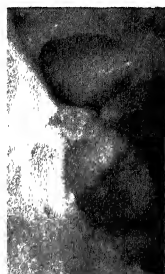
10.43C. A heart opened to show the aortic root as illustrated diagrammatically in figure 10.43A.

lateral profile of the right atrium. An upward continuation of this line marks the right border of the superior vena cava while a downward continuation corresponds to the border of the inferior vena cava. The lower border of the surface projection is a line joining the lower end of the right border to the apex beat. Corresponding largely to the lower (acute) margin of the right ventricle, it crosses over the xiphisternal joint to include the apical part of the left ventricle. The left border of the heart is marked by a line from the apex beat to the lower border of the left second costal cartilage approximately 1 cm from the sternal margin. It is convex upwards and to the left, corresponding to the obtuse margin of the left ventricle and to the left atrial appendage above. The border is completed superiorly by a sloping line joining the upper ends of the right and left borders, approximating to the upper limits of the atria. The left and right borders can be identified by heavy percussion.

The surface projection of the anterior part of the *atrioventricular groove* is an oblique line joining the sternal ends of the third left and sixth right costal cartilages. This line separates the atrial and ventricular areas. Although in different planes, the projections of the cardiac valves are also sited along or close to this line (10.46).

The *pulmonary orifice* is partly behind the superior border of the left third costal cartilage, and partly behind the left third of the sternum, being represented by a horizontal line, 2.5 cm long, crossing cartilage and sternum. Parallel lines from the ends of this line, up to the left second costal cartilage, indicate the site of the pulmonary trunk.

The *aortic orifice* is below and a little right of the pulmonary, marked by a line 2.5 cm long running from the medial end of the left third intercostal space downward to the right. Two parallel lines from the ends of this line, slanting up to the right half of the sternal angle, outline the location of the ascending aorta.

The *tricuspid valvar orifice* is represented by a line, 4 cm long, commencing near the midline just below the level of the fourth right costal cartilage and passing down and slightly to the right. The centre of this line should be level with the middle of the right fourth intercostal space.

The *mitral orifice* is behind the left half of the sternum opposite the fourth left costal cartilage and is represented by a line, 3 cm long, descending to the right.

Auscultation. As stated the foregoing are the approximate surface projections of the cardiac valves: they do **not** correspond to the sites for optimal auscultation of the contribution of each valve to the heart-sounds. To understand the latter an appreciation of the **position** and **plane** of each valve (the oscillator) must be combined with the geometry of its associated column of blood (in the ascending aorta, pulmonary trunk, right and left ventricles), which maximally carries the acoustic waveforms to the chest wall. Thus convenient sites to apply the stethoscope bell or diaphragm are:

- The *pulmonary area*, the sternal end of the second left intercostal space
- the *aortic area*, the sternal end of the second right intercostal space
- the *mitral* area, near the *cardiac apex*
- the *tricuspid area*, over the *centre* of the lower part of the *sternal body*, at the level of the fifth intercostal spaces.

*Commissural ring
(sinutubular junction)*

*Aortic wall within
ventricle (intercusp
triangle)*

*Ventriculo-arterial
ring and junction*

Ventricle within sinus

Basal ring
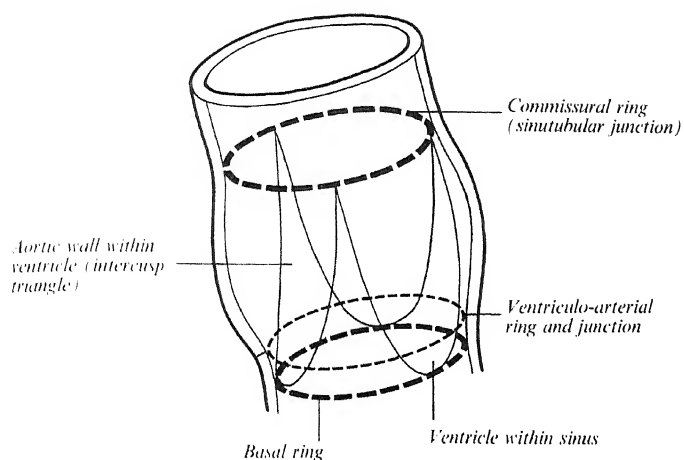
10.44 Diagram showing how the structure of the aortic root is best conceptualized in terms of a three-pronged coronet. There are at least three rings within this coronet, but none support the entirety of the attachments of the valvar leaflets (see also 10.43B).
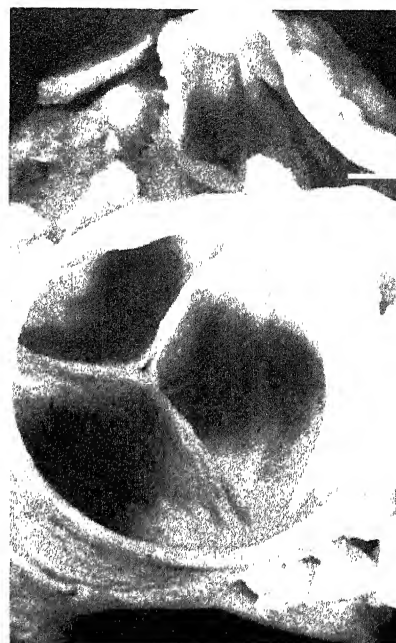
10.45 The arterial view of the aortic valve in its closed position shows the snug fit between its component leaflets.
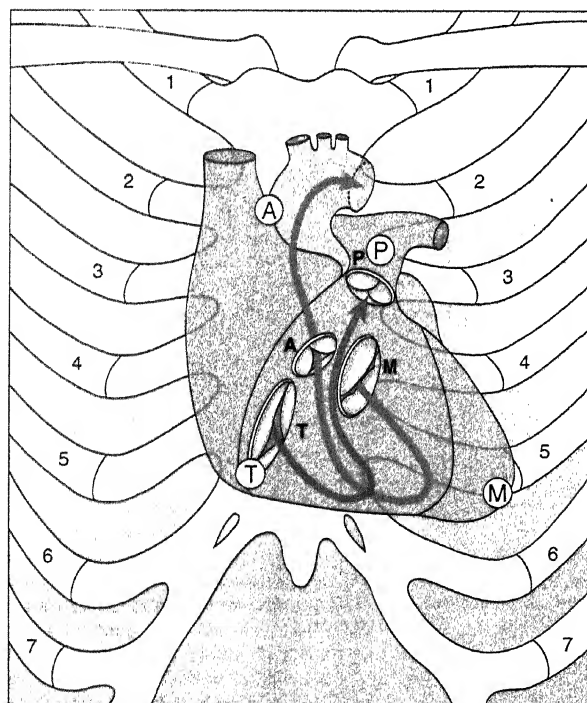
10.46 Diagram illustrating the relation of the sternocostal surface and valves of the heart to the thoracic cage. The right heart is blue, the arrow denoting the inflow and outflow channels of the right ventricle; the left heart is treated similarly in red. The positions, planes and relative sizes of the cardiac valves are shown. The position of the letters, A, P, T and M indicate the aortic, pulmonary, tricuspid and mitral auscultation areas of clinical practice. Note that, for purpose of illustration, the orifices of the aortic, mitral and tricuspid valves are shown with some separation between them. In reality, the leaflets of the three valves are in fibrous continuity (see 10.52).

*Position
trachea*

*Aortic
'knuckle*

*Pulmon
vessels o
right sia*
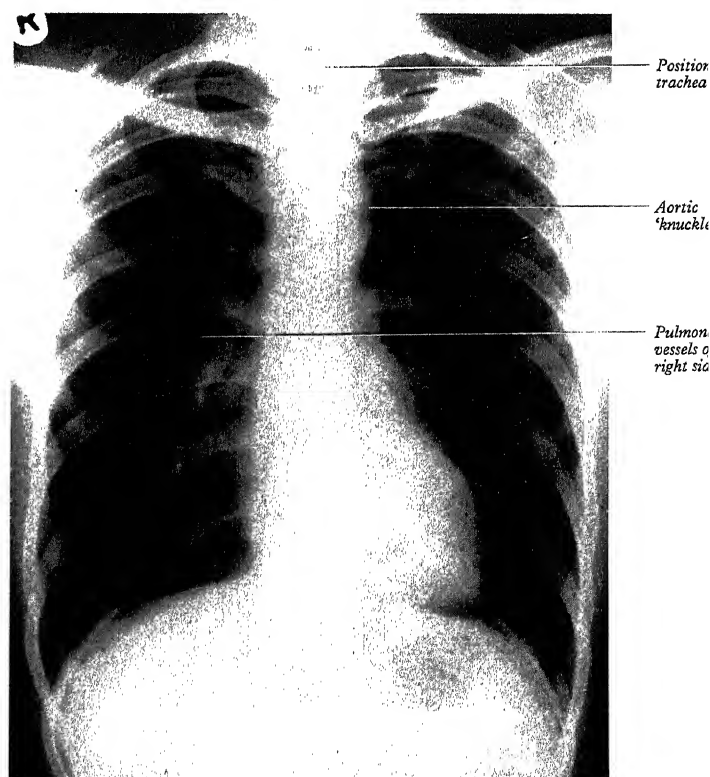
10.47 Radiograph of chest, postero-anterior view, of adult male. Note the difference in level of the right and left halves of the diaphragm. (Supplied by Shaun Gallagher, Guy's Hospital.)
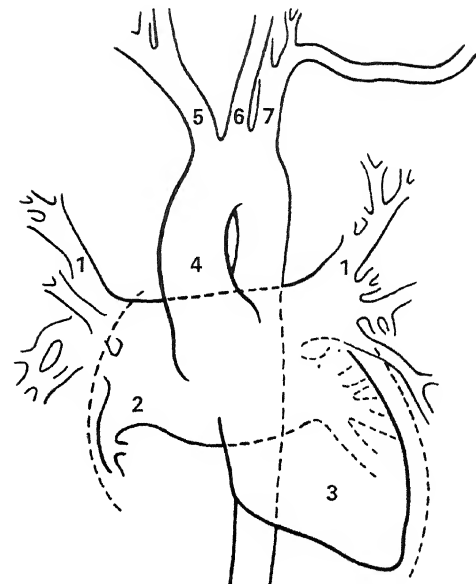
10.48 Angiocardiogram showing the left side of the heart in a child of 11 years; anteroposterior view. 1. Upper pulmonary vein. 2. Left atrium. (Note that owing to the great obliquity of the atrial septum, the left atrium extends to the right behind the right atrium). 3. Left ventricle. 4. Ascending aorta. 5. Brachiocephalic trunk. 6. Left common carotid artery. 7. Left subclavian artery. The arms of the patient are raised above the head and as a result the distal end of the artery passes upwards. (Provided by Frances Gardner.)
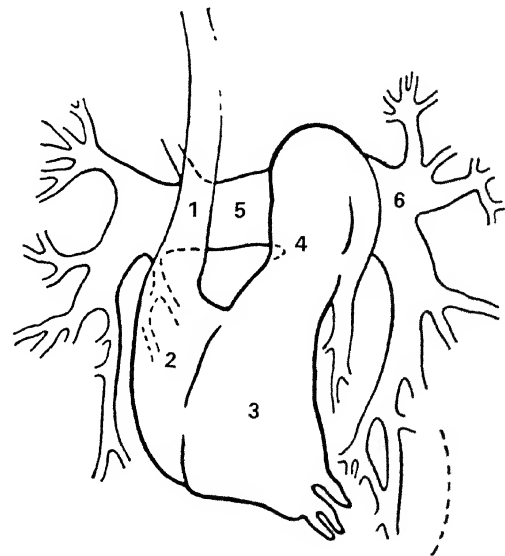
10.49 Angiocardiogram showing the right side of the heart in a child of 12 years; anteroposterior view. 1. Superior vena cava. 2. Right atrium. 3. Right ventricle. 4. Pulmonary trunk. 5. Right pulmonary artery. 6. Left pulmonary artery. (Provided by Frances Gardner.)

The area of superficial cardiac dullness as mapped out by light percussion is roughly triangular and corresponds to the area of the heart not covered by lung.

RADIOLOGICAL APPEARANCES OF THE HEART

The heart, being full of blood, casts a shadow, occupying the inferior mediastinum, which is in sharp contrast to those areas occupied by the air-filled lungs (**10.47**). In full inspiration, the apex is clear of the diaphragm, presenting a blurred outline in radiographs due to movement. The right border of the shadow is continuous with those of the venae cavae. Due to the attachment of the pericardium to the diaphragm, the heart elongates during inspiration and shortens during expiration. The cardiac shape also varies with stature and attitude (p. 1734). In lateral radiographs, the retrocardiac space is a translucent area between the heart and the vertebral column, occupied by the descending aorta and the oesophagus. Angiography was, and is, used routinely for detailed study of the cavities and larger

Electrocardiogram

Anterior wall of right ventricle

Cavity of right ventricle

Interventricular septum

Cavity of left ventricle

Leaflets of mitral valve

Posterior wall of left ventricle

10.50 A standard M (motion) mode echocardiogram recorded from the parasternal window. This technique, now supplemented in clinical practice by so-called 2-D formats, shows the movement of the parietal walls, ventricular septum and mitral valvar leaflets as indicated in the accompanying diagram. Note the biphasic nature of closure of the mitral valve.

vessels (**10.48, 49**). Nowadays, nonetheless, use of angiography is, in some centres, being supplemented, and sometimes replaced, by non-invasive studies such as computerized tomography (CT), echocardiography (**10.50**), and magnetic resonance imaging (MRI). Interpretation of the images is unchanged and depends on knowledge of the location of the cardiac structures within the body.

CONNECTIVE TISSUES AND FIBROUS SKELETON OF THE HEART

From epicardium to endocardium, and from the orifices of the great veins to the roots of the arterial trunks, the intercellular spaces between contractile and conducting elements are everywhere permeated by connective tissue. The amount varies greatly in arrangement and texture in different locations.

A fine layer of areolar tissue is found beneath the mesothelium of the serosal visceral epicardium over much of the heart (**10.23**). This accumulates *subepicardial fat*, the amount increasing with age, which becomes concentrated along the acute margin, the atrioventricular and interventricular grooves and their side channels. The coronary vessels and their main branches are embedded in this fat. The endocardium also lies on a fine areolar tissue, this time rich in elastic fibres. Fibrocellular components of these subepicardial and subendocardial layers blend on their mural aspects with the endomysial and perimysial connective tissue on the myocardium. Each cardiac myocyte is invested by delicate endomysium composed of fine reticular fibres, collagen and elastin fibres embedded in ground substance. This matrix is lacking only at desmosomal and gap junctional contacts of intercalated discs (p. 768). Similar arrangements apply to myocytes of the ventricular conduction tissues and their extensive contacts with the working myocardium. The connective tissue matrix itself is interconnected laterally to form bundles, strands or sheets of macroscopic proportions showing a complex geometric pattern (p. 1496). The larger myocardial bundles are surrounded by, and attached to, stronger perimysial condensations. The overall pattern is described in terms of struts and weaves.

The myocardial matrix, despite its importance, cannot be dissected grossly. Running at the ventricular base, nonetheless, and intimately related to atrioventricular valves and the aortic orifice, is a complex framework of dense collagen with membranous, tendinous and fibro-areolar extensions. The whole is sufficiently distinct to be termed the fibrous skeleton of the heart. (For detailed analyses see Zimmerman & Bailey 1962; Zimmerman 1966).

Although it is often stated that all four valves are contained within this skeleton, this is not the case. The cusps of the pulmonary valve are supported on a free-standing sleeve of right ventricular infundibulum which can easily be removed from the heart without disturbing either the fibrous skeleton or the left ventricle. The fibrous skeleton, rather, is strongest at the junction of aortic, mitral and tricuspid valves, the so-called *central fibrous body* (**10.51, 52**). Two pairs of curved, tapering, collagenous prongs (*fila coronaria*) extend from the central fibrous body, stronger on the left, passing partially around the mitral and tricuspid orifices, which are almost coplanar and incline to face the cardiac apex. The aortic valve, in contrast, faces up, right and slightly forwards. It is anterosuperior to and rightward of the mitral orifice. As already described, two of the cusps of the aortic valve are in fibrous continuity with the aortic leaflet of the mitral valve. This *aortic-mitral* or *subaortic curtain* (**10.43B, 51**) is also an integral part of the fibrous skeleton. The two ends of the curtain are strengthened as the *right* and *left fibrous trigones*, which are the strongest part of the skeleton. The *right trigone*, together with the membranous septum, then constitutes the *central fibrous body* (**10.51**). This important structure is penetrated by the mechanism for atrioventricular conduction (the bundle of His) while the membranous septum is crossed on its right aspect by the attachment of the tricuspid valve, dividing the septum into atrioventricular and interventricular components.

The functions of the fibrous skeleton are, first, to ensure electrophysiological discontinuity between the atrial and ventricular myocardial masses except at the site of penetration of the conduction tissue. Second, it functions as a stable but deformable base for the attachments of the fibrous cores of the atrioventricular valves.

The aortic root is central within the fibrous skeleton and, as discussed, is often described in terms of an '*annulus*' integrated within the fibrous skeleton. As with the pulmonary valve, nonetheless, the structure of the aortic root corresponds to the triple fibrous semilunar attachments of its cusps. Within this complex circumferential zone are three crucially important triangular areas which separate, on the ventricular aspect, the aortic bulbous sinuses which house the valvar cusps. As a whole, these three triangles can be conceptualized in terms of a three-pointed coronet (**10.44**). These triangular areas were termed the *subaortic spans* by Zimmerman (1959), Zimmerman and Bailey (1962), but were originally described as the intervalvular spaces by Henle (1876). Their triangular apices correspond to the tips of the valvar commissures. Their walls, significantly thinner than the sinuses, variously consist of collagen or admixed muscle strands and fibro-elastic tissue. They form the subvalvar extensions of the aortic vestibule. The interval between the non-coronary and left coronary sinuses is filled with the deformable *subaortic curtain*. The span between the non-coronary and right coronary sinuses is continuous with the anterior surface of the *membranous septum*. The

Pulmonary valve

Trigonum fibrosum sinistrum

Anterior cusp of mitral valve

Subaortic curtain

Tendon of the infundibulum

Parts of triple-scalloped aortic annulus

Atrioventricular bundle

Anterior cusp of tricuspid valve

Trigonum fibrosum dextrum

10.51 The base of the ventricles, after removal of the atria and the pericardium. Contrast the planes and positions of aortic and pulmonary valves. Contrast with **10.52**. (From Walmsley 1929.)

third subaortic span, namely that between the two coronary aortic sinuses, is filled with fibro-elastic tissue that separates the extension of the subaortic root from the wall of the free-standing subpulmonary infundibulum. Previously this was held to be the location of the *tendon of the infundibulum (conus ligament)*. Similar fibrous triangles are found separating the sinuses of the pulmonary trunk, but these are significantly less robust.

The *mitral* and *tricuspid rings (annuli)* (pp. 1481, 1485), are also not simple and rigid collagenous structures but dynamic, deformable lines of valvar attachment that vary greatly at different peripheral points and change considerably with each phase of the cardiac cycle and with increasing age. The tricuspid attachments are even less robust than those of the mitral valve. At several sites it is only fibro-areolar tissue which separates the atrial and ventricular muscular masses.

ARCHITECTURE OF THE MYOCARDIUM

It has long been held that cardiac walls consist of 'fibres' transversely and longitudinally striated (p. 764) and intricately intermingled. They can be classed as atrial, ventricular, and conduction fibres (p. 1495). Atrial and ventricular muscle fibres are completely separated at the atrioventricular grooves, the only connection being via the axis of specialized myocardial cells responsible for atrioventricular conduction. The fibres of the working myocardium, atrial and ventricular, are aggregated by the fibrous matrix into well-organized rows and bundles (**10.53, 54**).

The *atrial fibres* are arranged in two layers: a superficial layer common to both atria and a deep layer proper to each. The *superficial fibres* are most distinct anteriorly where they cross the bases transversely as a thin, incomplete layer. Superiorly, the walls themselves are infolded to form the rim of the atrial septum. Deep fibres are looped and annular. The looped fibres pass over each atrium to its corresponding atrioventricular annulus, in front and behind, while annular fibres surround the appendages and encircle the openings of the venae cavae and the fossa ovalis. Further well-organized bundles are found within the terminal crest of the right atrium and its pectinate muscles.

The arrangement of the *ventricular fibres* within the ventricular mass is much more complicated, and has been the focus of many investigations over the years. Most of these have involved prior maceration or boiling of the hearts investigated, followed by dissection or tearing apart of the ventricular walls. Of necessity, these techniques are somewhat crude. Although they can produce remarkably photogenic specimens, they all suffer from the difficulty of distinguishing true tracts of fibres from artefactually induced pathways.

Combinations of dissections with study of orientations of fibres as measured in serial sections give a more accurate impression of the interrelationships of the musculature (Streeter et al 1969, 1983; Greenbaum et al 1981). These works have shown that earlier concepts, such as those espoused by MacCallum (1900) and Mall (1911), placed undue emphasis on the fibrous skeleton as the site of origin and insertion of the ventricular fibres. The heart is not to be compared with a skeletal muscle. Rather, it is a modified blood vessel. The myocardial fibres, in consequence, are attached to their neighbours and bound together by the fibrous matrix. The skeleton serves the purpose of anchoring the valves to the ventricular mass and, as discussed above, is significantly less well formed than is generally believed. Thus, concepts of the ventricular musculature being arranged in tracts which originate at the atrioventricular annulus and insert into the bases of the arterial trunks have little to support them in terms of anatomic fact. The dissections performed, which are backed up by histological studies, largely endorse the accounts of Pettigrew (1860, 1865).

The dissections show that the fibres can broadly be divided into subepicardial, middle, and subendocardial fibres. Simple inspection of the heart after the removal of the epicardium reveals the arrangement of the subepicardial fibres. By and large, these fibres run circumferentially around the right ventricle and longitudinally down the diaphragmatic surface of the left ventricle. Fibres cross over the posterior interventricular groove, and more complicated cross-over fibres are found at the anterior atrioventricular groove which continue into the free-standing subpulmonary infundibulum.

Superficial fibres also form vortices at the apices of both ventricles, turning in to form subendocardial fibres as well described by Mall (1911) (**10.53**). The middle fibres, arranged circumferentially, are confined to the left ventricle and the septum, the parietal wall of the right ventricle having only superficial subepicardial and deep subendocardial fibres. The greatest thickness of circumferential fibres is found at the base of the left ventricle, where they encircle the inlet and outlet components. This is the layer dubbed the 'bulbospiral' muscle by earlier investigators. The subendocardial layers of both ventricles are continuous with the subepicardial fibres through the apical vortexes. These deep fibres form a thin layer in the left ventricle except where buttressed to form the papillary muscles. The fibres within the trabeculae run almost longitudinally, while those closer to the middle layer take an oblique course. The papillary muscles are less robust in the right ventricle. The septum belongs largely to the left ventricle, being formed for its greatest part by the circumferential layer of middle fibres (**10.38**). Since these circumferential fibres are lacking towards the ventricular apex, the apical septum is formed only by the co-apted subendocardial layers as they turn in from the ventricular apexes. There are major regional
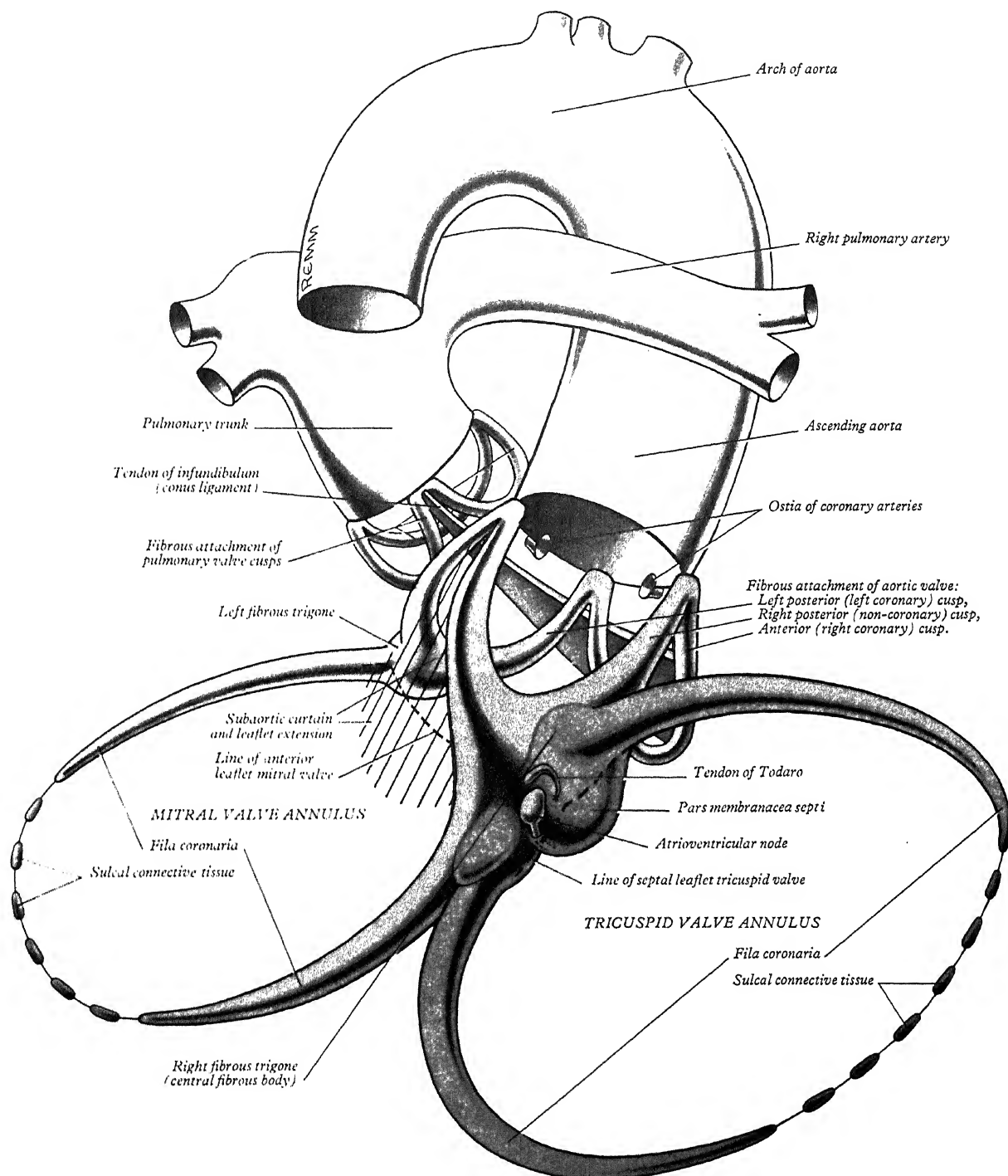
10.52 Principal elements of the fibrous skeleton of the heart: red = mitral and aortic 'annuli', blue = tricuspid and pulmonary 'annuli', green = tendon of the infundibulum. For clarity the view is from the right posterosuperior aspect. Note that due to perspective the pulmonary annulus appears smaller than the aortic annulus, whereas in fact the reverse obtains. Based in part on the work of Zimmerman (1966). Consult text for an extended discussion.

variations in the arrangement of the fibres from heart to heart. Even greater departures from this variable 'norm' are found in hearts diseased due to dilatation, hypertrophy, coronary arterial disease, or congenital malformations. Much more work remains to be done before the true organization of the ventricular fibres is elucidated.

That which has been accomplished in recent years simply underlines the potential dangers inherent in imposing procrustean and oversimplified ideas on a complex biological structure (Greenbaum et al 1981).

CO-ORDINATION OF CARDIAC ACTIVITY: CONDUCTION SYSTEM

The human heart beats ceaselessly at about 70 or so cycles every minute for many decades, maintaining perfusion of pulmonary and systemic tissues. The rate and stroke volume fluctuate in accord with prevailing physiological demands. The principal events in a cardiac cycle, including the electrical events recorded in the electro-
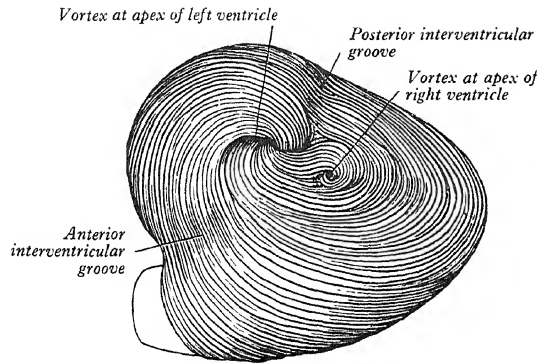
10.53 The two vortices in the myocardium at the apex of the heart (after Mall).

cardiogram (ECG), mechanical sequences of diastole, atrial systole, isovolumetric contraction, ejection and isovolumetric relaxation in ventricular systole, the acoustic phenomena recorded in the phonocardiogram, pressure profiles of right and left hearts and arterial trunks and the sequences of valvar events are summarized in **10.55**. Cardiac efficiency depends on precise timing of the operation in interdependent structures. Passive diastolic filling of the atria and ventricles is followed by atrial systole, stimulated by discharge from the sinus node, which completes ventricular filling. Excitation and contraction of the atria must be synchronous and finish prior to ventricular contraction. This is effected by a **delay** in the conduction of excitation from atria to ventricles. Thereafter, ventricular contraction proceeds in a precise manner, a specialized ventricular conduction system ensuring that closure of atrioventricular valves is followed rapidly by a wave of excitation and contraction spreading from the ventricular apices towards the outflow tracts and orifices, rapidly accelerating the blood during ejection.

Vertebrate cardiac contraction originates unequivocally in specialized myocytes, but neural influences are important in adapting the intrinsic cardiac rhythm to functional demands from the whole body. All cardiac myocytes (p. 764) are excitable, with autonomous rhythmic depolarization and repolarization of the cell membrane, conduction of waves of excitation via gap junctions to adjacent myocytes, and excitation-contraction coupling to their actomyosin complexes (p. 774). These properties are developed to different degrees in different sites and in different types of myocyte. The rate of depolarization and repolarization is slowest in the ventricular

myocardium, intermediate in the atrial muscle, and fastest in the myocytes of the sinus node. The latter override those generating slower rhythms and, in the normal heart, are the locus for the rhythmic initiation of cardiac cycles. Conversely, conduction velocity is slow in nodal myocytes, intermediate in general 'working' cardiac myocytes and fastest in the myocytes of the ventricular conduction system.

The nodes and networks of the so-called specialized myocardial cells constitute the *cardiac conduction system* (10.56A, B, 57). The components of the system are the sinus node, the atrioventricular node, the atrioventricular bundle with its left and right bundle branches, and the subendocardial plexus of ventricular conduction cells (Purkinje fibres). Remnants of histologically specialized cells are also found at the insertions of right atrial myocardium into the atrioventricular junction. These are remnants of the more extensive conduction system found in the developing heart, and are described as *atrioventricular ring tissues*. Comprehensive accounts of the cardiac conduction system are found in Hudson (1965) and Anderson & Becker (1980).

Sinus node of Keith and Flack (1907)

The cardiac 'pacemaker', it initiates (in some of its cells) each cardiac cycle. It is located at the junction between parts of the right atrium derived from the embryonic venous sinus and the atrium proper (10.56A, 57). The node is distinctive histologically, with very short transitional zones peripherally. Nodal tissue does not occupy the full thickness of the right atrial wall from epicardium to endocardium in humans, but rather sits as a wedge of specialized tissue subepicardially within the terminal groove. The node is often covered by a plaque of subepicardial fat, making it visible in some instances to the naked eye. It extends between 1 and 2 cm on the right from the crest of the right auricle and runs postero-inferiorly into the upper part of the terminal groove. In a small proportion of cases, about one-tenth, it extends in horse-shoe fashion across the crest of the auricle. An obvious feature of the node is its *central artery*. This has a surprisingly large calibre and takes its origin from either the right or the circumflex coronary arteries. Usually originating from the initial segments of these arteries, it rarely takes a more distal origin which then places it at risk during routine opening of the atrium in the course of cardiac surgery. Its adventitia merges into a dense collagenous reticulum which permeates the node and surrounds its myocytes. Its small lateral branches supplying nodal tissue are few, the vessel continuing beyond the node to ramify in the atrial myocardium. The *nodal myocytes* themselves are slender and fusiform. Such nodal myocytes themselves are confined to the nodal centre, circumferentially arranged around the nodal artery and more irregularly placed external to this. These cells are now considered the 'pacemakers'. They make functional contacts with each other and adjacent transitional myocytes, which are smaller than the general myocardial cells. There are only short transitional zones at the margin of the node, the junction with plain atrial myocardium being clear cut.
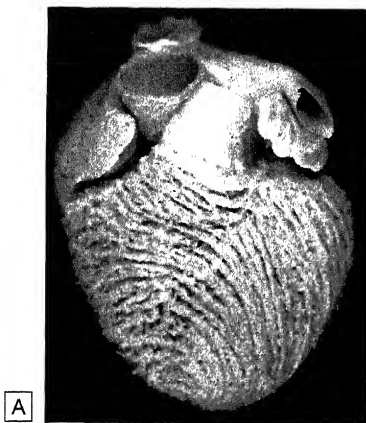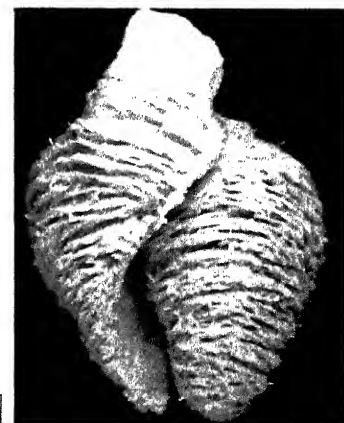
10.54A, B. These standard dissections of the ventricular mass show the superficial layer of fibres extending over the anterior surface of both ventricles (A). In B further dissection reveals the important middle layer of circumferential fibres (the 'bulbospiral muscle') which is confined to the left ventricle. Dissection made by Professor Damian Sanchez-Quintana, Badajoz, Spain, and reproduced by kind permission.

PRESSURE (mm/Hg) IN LEFT SIDE OF HEART

100
80
60
40
20
0

10.55 Diagram summarizing some of the principal events occurring in the cardiac cycle that are mentioned at various points throughout the text.

Aorta

Left atrium
Left ventricle

PRESSURE IN RIGHT SIDE OF HEART

20
0

Pulmonary artery
Right atrium
Right ventricle

MECHANICAL ACTIVITY

LEFT
RIGHT

ATRIUM

VENTRICLE
EJECTION
EJECTION

Stipple marks isometric contraction and relaxation

SEQUENCE OF VALVE MOTION

)Closure of mitral valve

⑤ Closure of aortic valve

)Closure of tricuspid valve

⑥ Closure of pulmonary valve

of pulmonary valve

⑦ Opening of tricuspid valve

ing of aortic valve

⑧ Opening of mitral valve

PHONOCARDIOGRAM

First heart sound

Second heart sound

ELECTROCARDIOGRAM

R
P
Q S
T

TIME SCALE

0   0·1   0·2   0·3   0·4   0·5   0·6   0·7 sec.

A

Aorta

Right pulmonary artery

Bachman's bundle

Superior vena cava

Sinuatrial node

Fossa ovalis

Tendon of Todaro

Valve of inferior vena cava

Coronary sinus

Inferior vena cava

Right auricular appendage

Pulmonary valve

Torus aorticus

Pars membranacea septi (atrio-ventricular part)

Radiation of left 'bundle' branch

Right bundle branch

Atrioventricular node

Septal cusp of tricuspid valve

Septomarginal trabecula (Moderator band)

Papillary muscles

Cut chordae tendinae of mitral valve

Left auricular appendage

Aorta

Pulmonary trunk

Anterior papillary muscle

Right pulmonary veins

Aortic valve

Inferior vena cava   Radiation of left 'bundle' branch

10.56 Diagrams of the conducting tissue of the heart as seen from the right (A) and left (B) aspects. The elements of the conducting system are shown in red. Note the conducting tissue accompanying fine trabeculae carneae and false chordae. Please note that in reality the radiation of the left bundle branch is directly related to the leaflets of the aortic valve.
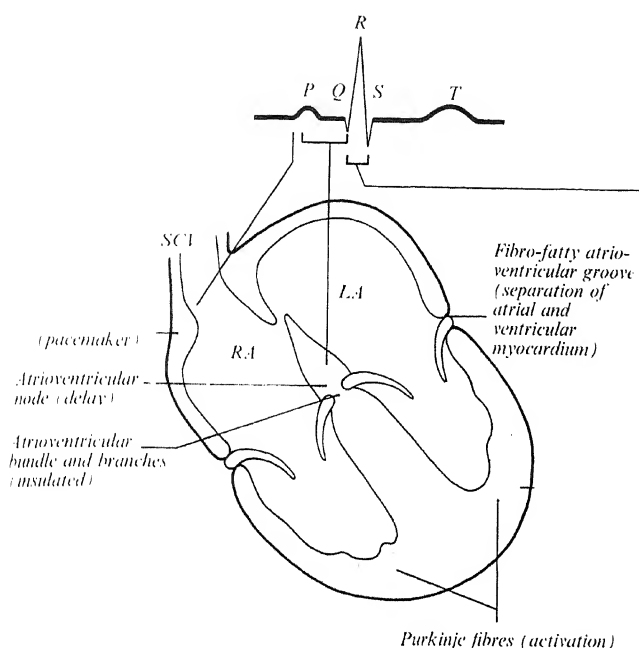
10.57 A diagram illustrating the basic structure of the conduction system, and showing the relationship with the electrocardiogram.

Atrioventricular node (Tawara 1906)

The atrioventricular node is an atrial structure which is at the root of an extensive tree of conduction tissue reaching the apex of the ventricles, the papillary muscles and other regions of the ventricles (10.57). The node, with its transitional zones, is located within the atrial component of the muscular atrioventricular septum, the anatomic landmarks being the boundaries of the triangle of Koch (10.56A). These are, inferiorly, the attachment of the septal leaflet of the tricuspid valve, basally the orifice of the coronary sinus and, superiorly, the tendon of Todaro. The compact node is a half oval set against the central fibrous body towards the apex of this triangle. Its atrial aspect is convex, being overlain by atrial myocardium. Its left margin is concave and abuts on the superior aspect of the central fibrous body. Its basal end projects into the atrial muscle while its antero-inferior end enters the central fibrous body to become the penetrating atrioventricular bundle. The node is pervaded by an irregular collagenous reticulum enmeshing the myocytes, but this is less dense than in the sinus node. Its arterial supply is from a characteristic vessel originating from the dominant coronary artery at the crux of the heart. The node has a well-formed compact zone made up of interlocking nodal cells which frequently show stratification. Superficially and posteriorly are found the transitional cell zones. The larger component of atrioventricular delay is probably produced in these transitional zones of the node.

Atrioventricular bundle

Originally described by His (1893) but clarified by Tawara (1906), the atrioventricular bundle is the direct continuation of the atrioventricular node, becoming oval, quadrangular or triangular in transverse sectional profile as it enters the central fibrous body (10.56A, p. 1493). Traversing the fibrous body, it branches on the crest of the muscular interventricular septum, the branching tract being sandwiched between the muscular and the membranous components of the septum. The *right branch* of the bundle (*crus dextrum*) is a narrow, discrete round group of fascicles which courses at first within the myocardium and then subendocardially towards the apex of the ventricle, entering the septomarginal trabecula to reach the anterior papillary muscle. It has few branches to the ventricular walls in its septal course, but, at the origin of the anterior papillary muscle, it divides profusely into fine subendocardial fascicles which diverge and embrace, first, the papillary muscle, then, recurving

subendocardially to the remaining ventricular walls. The *left branch* (*crus sinistrum*) arises as numerous fine intermingling fascicles which leave the left margin of the branching bundle through much of its course along the crest of the muscular ventricular septum (10.56B). These fascicles form a flattened sheet down the smooth left ventricular septal surface. The sheet diverges apically and subendocardially across the left aspect of the ventricular septum, separating into anterior, septal and posterior divisions. Fine branches leave the sheets, forming subendocardial networks, which first surround the papillary muscles and then curve back subendocardially to reach all parts of the ventricle.

The principal branches of the bundle are insulated from the surrounding myocardium by sheaths of connective tissue (10.58). Functional contacts between ventricular conduction and working myocytes become numerous only in the subendocardial terminal ramifications. Hence, papillary muscles contract first, followed by a wave of excitation and ensuing contraction travelling from the apex of the ventricle to the arterial outflow tract. And, because the Purkinje network is subendocardial, muscular excitation proceeds from the endocardial to the epicardial aspect. In the developing heart, it can be shown that the bundle responsible for atrioventricular conduction is a much more extensive structure (Wessels et al 1992). Recent work using immunohistochemical markers has shown that the precursor of the system is a ring of cells which surrounds the inlet and outlet components of the developing ventricular loop (see p. 308). With septation of the ventricles, this ring becomes modified so that it encircles the right atrioventricular orifice and the aortic outlet from the left ventricle. With subsequent growth, only the septal components of this 'figure of eight' persist as the atrioventricular conduction tract. Careful study, nonetheless, reveals that part of the aortic ring can persist as a 'dead-end tract' (Kurosawa & Becker 1985).

The components initially surrounding the tricuspid orifice also persist to varying degree, and can be found by careful study in most human hearts. These nodes of unequivocally specialized tissue are identical to the structures described and illustrated by Kent at the turn of the nineteenth century (1893, 1913). Kent was convinced that these structures were the substrates for normal atrioventricular conduction, which, he argued, occurred at multiple points around the atrioventricular junction. This contention is incorrect, and the remnants found as atrioventricular ring tissue are always sequestrated by the fibrous insulation mechanism from the ventricular myocardium. Kent's findings, nonetheless, provided the stimulus for clinicians to explain the abnormal cardiac rhythm known as ventricular pre-excitation, specifically the variant known as the Wolff-Parkinson-White syndrome. It has now been shown that this syndrome is produced by abnormal small strands of otherwise unremarkable ventricular myocardium which connect the atrial and ventricular myocardial masses at some point around the atrioventricular junctions. Initially these muscular strands were described

10.58 Section of conducting, Purkinje fibres in the left ventricular wall. Note the paler, enlarged cells beneath the endocardium among normal (or 'working') myocytes. Haematoxylin and eosin. Magnification × 500.

as 'bundles of Kent', the belief being that they represented the multiple connections postulated by Kent. When the connections were identified histologically, it was seen that they bore no resemblance to the remnants of atrioventricular ring tissue initially described by Kent. Instead, they were strands of working myocardium running through the fibro-areolar tissue of the atrioventricular groove.

Sinus node, atrioventricular node and atrioventricular bundle constitute a well-defined anatomical system; in it the main pacemaker rhythm of the heart is generated (sinus), is influenced by nerves (sinus and its innervation) and is transmitted specifically from atria to ventricles (atrioventricular node and bundle) and, within the ventricles, to all their musculature. The spread of excitation is very rapid but not instantaneous: different parts of the ventricles are excited at slightly different times, with important functional consequences. Failure of the conduction system will not block cardiac contraction, but this will become poorly co-ordinated or unco-ordinated; the rhythm will be slower as it then originates from a spontaneous (myogenic) activity in the working cardiac myocytes or in a subsidiary pacemaker in a more distal part of the diseased or disrupted conduction system.

One important question in this account of the role of the conduction system is: how does the excitation generated by the sinus reach the atrioventricular node? There has been considerable debate and controversy on this issue since the beginning of the century, when there were reports on the occurrence of bundles of specialized cardiac myocytes in the atria, connecting the sinus to the atrioventricular node and the right to the left atrium. Although only Thorel (1909) truly claimed to have distinguishd specialized tracts, two other tracts have been attributed to Wenckebach (1906) and Bachmann (1913). The latter workers, although describing tracts, made no claims concerning histological specialization. Furthermore, subsequent studies of the atrial walls have failed to show the existence of specialized muscle tissue, such as can be readily seen in the atrioventricular bundle. Modern authors, therefore, dismiss the occurrence of any specialized internodal and interatrial conduction pathways (Anderson et al 1974; Anderson 1975). In the absence of specialized internodal and interatrial conduction pathways, the excitation emanating from the sinus node spreads to the atrial musculature and to the atrioventricular node through ordinary atrial working myocardium. The studies of Spach and Kootsey (1983) have confirmed that there are no anatomically specialized pathways comparable with the ventricular system responsible for conduction. Instead, it is the packing and the geometric arrangement of fibres along well-organized atrial muscle bundles, such as the terminal crest and the rims of the oval fossa, which are responsible for conduction being marginally more rapid than elsewhere within the atrium. The muscle fibres responsible for such conduction, as far as can be judged with standard staining, are ordinary working atrial myocardial fibres (Janse & Anderson 1974).

NERVE SUPPLY TO THE HEART

Initiation of the cardiac cycle in vertebrates is myogenic, originating in the sinus node. The cardiac cycle initiated in this fashion is harmonized in rate, force and output by nerves of the autonomic nervous system operating on the nodal tissues and their prolongations, on coronary vessels and on the working atrial and ventricular musculature. This supply is autonomic, and has both efferent (sympathetic and parasympathetic) and afferent components. Parasympathetic fibres reach the heart through vagal branches (p. 1252), the sympathetic from the branches of the sympathetic trunk (p. 1303). Vagal preganglionic fibres proceed from origins within the brainstem, particularly the medulla, including the nucleus ambiguus (p. 1021), the reticular nuclei (p. 1073) and possibly the dorsal vagal nucleus (p. 1020). Preganglionic axons leave in the cardiac branches of both the right and the left vagus nerves to reach the cardiac plexus. Sympathetic preganglionic neurons are in the upper five or six segments of the intermediolateral column of the thoracic spinal cord (Kuntz 1953). These fibres end in the cervical and the third and fourth thoracic sympathetic ganglia (Mitchell 1953), from all of which postganglionic fibres proceed bilaterally to the heart (pp. 1252, 1306). (See also general comments and modern reservations concerning the simplification implicit in the terms pre- and postganglionic, p. 1293.)

The central connections of cardiac preganglionic neurons, parasympathetic and sympathetic, are described elsewhere (Reticular formation of the brainstem p. 1073, Hypothalamus p. 1094 and Cerebral cortex p. 1141). The existence and behaviour of these integrating influences can be deduced in terms of their function, but the precise locations of connecting pathways in the spinal cord, brainstem, and cerebrum are uncertain.

Nearing the heart, the autonomic nerves form a mixed cardiac plexus (p. 1306), usually described in terms of a superficial component found inferior to the aortic arch and between it and the pulmonary trunk, and a deep part between the aortic arch and tracheal bifurcation. These plexuses contain ganglion cells, with further ganglion cells found in the heart along the distribution of branches of the plexus (10.59). The branches of these cells are considered largely, if not exclusively, postganglionic and parasympathetic in nature. The advent of more reliable staining techniques for identification of cholinergic and adrenergic nerve cells and their ramifications has now helped clarify the distribution of cardiac autonomic components, although the discovery of additional neural transmitters which are neither truly cholinergic nor adrenergic has added a further complicating element (Corr 1992).

Cholinergic and adrenergic fibres, arising in or passing through the cardiac plexus, are distributed most profusely to the sinus and atrioventricular nodes, with a much less dense supply to the atrial and ventricular myocardium. Adrenergic fibres supply the coronary arteries and cardiac veins. Rich plexuses of nerves containing cholinesterase, adrenergic transmitters, and other peptides such as neuropeptide Y (NY) are found in the subendocardial regions of all chambers and in the leaflets of the valves. Complex endorgans have also been discovered in the subendocardium of the left atrium (Tranum-Jensen 1975).

Ganglion cells, the source of vagal postganglionic fibres, are confined to the atrial tissues in man, with a preponderance adjacent to the sinus node. Some ganglion cells in the atrium have now been shown to contain adrenergic transmitters, and they also contain small, intensely-fluorescent chromaffin cells (SIF-cells, see p. 1299).

Arteries of cardiac supply, the aortic coronary branches, are described on pages 1495–1510, cardiac veins and the coronary sinus on pages 1575–1576 and lymphatic drainage on page 1625.

Fetal blood reaches the placenta via two umbilical arteries and
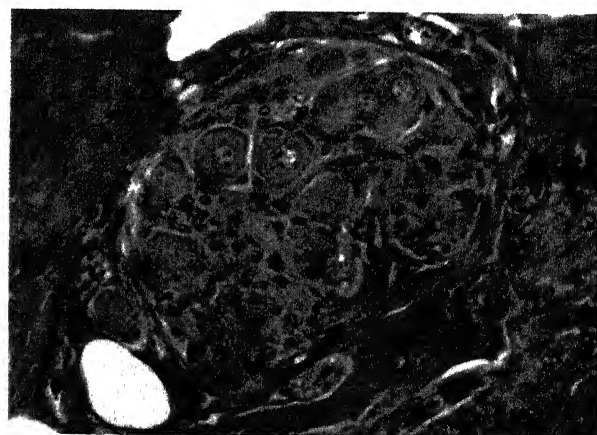
10.59 Small autonomic nerve ganglion in the wall of the left atrium (monkey). The ganglion lies within the atrial musculature; several ganglion neurons are grouped together, and each of them is surrounded by small satellite cells (glial cells). Masson trichrome stain. Magnification × 600.

Superior vena cava

Right lung

Right atrium

Right lobe
of li;

Portal vein

Persistent left
umbilical vein

Umbilical
vein

Left
umbilical
artery

Arch of aorta

Ductus
arteriosus

Pulmonary trunk

Left lung

Left atrium

Left ventricle

Right ventricle

Left lobe of
liver

Venous duct

Inferior vena
cava

Aorta

Bladder
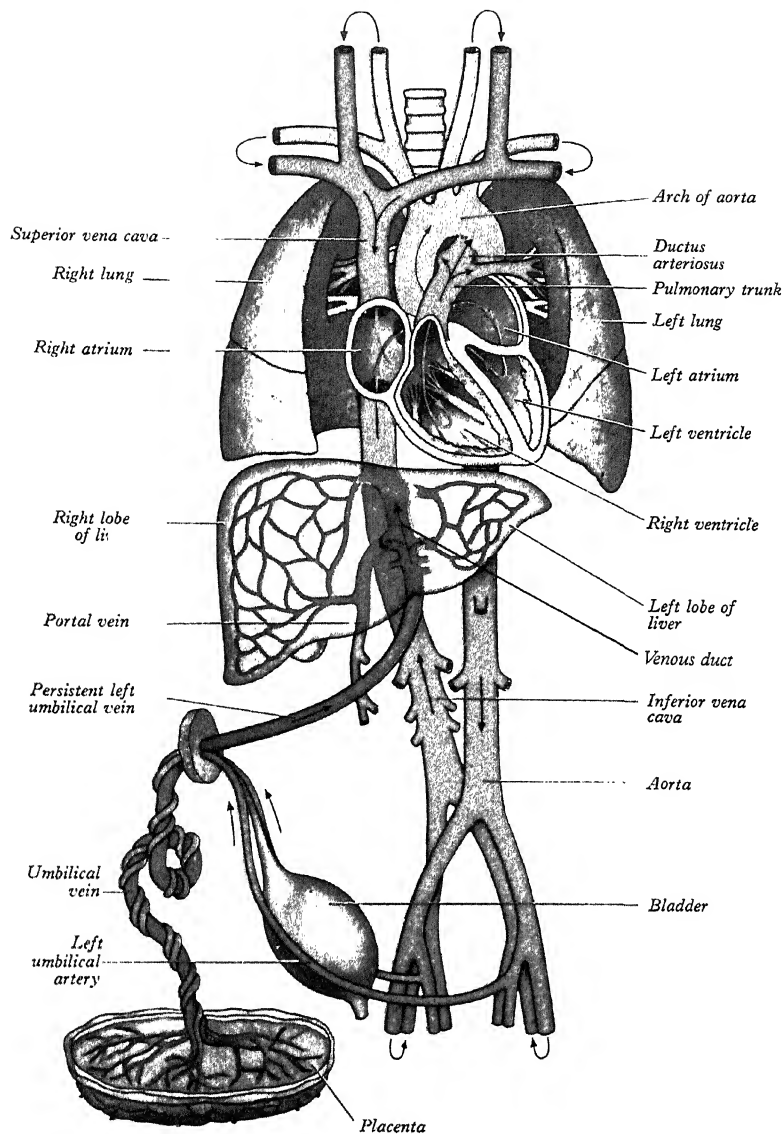
Placenta

10.60   Plan of the fetal circulation. The arrows indicate the direction of blood flow. The placenta is drawn to a greatly reduced scale.

returns in early fetal life by two umbilical veins (10.60). Later, the right one disappears (p. 324). The persisting left umbilical vein enters the abdomen at the umbilicus and traverses the edge of the falciform ligament to reach the hepatic surface of the liver. It then joins the left branch of the portal vein at the hepatic portal. Opposite the junction, a large vessel, the *venous duct* (*ductus venosus*), arises and ascends posterior to the liver to join the left hepatic vein near its termination in the inferior vena cava. (For a detailed developmental account, with illustrations, of the circumhepatic veins see p. 321.) The portal vein is small in the fetus compared with the size of the umbilical vein. Parts of its left branch, proximal and distal to their junctions, function as branches of the portal vein, carrying oxygenated blood to the right and left parts of the liver. Hence, blood in the left umbilical vein reaches the inferior vena cava by three routes:

• Some enters the liver directly and reaches the vena cava via the hepatic veins
• A considerable quantity circulates through the liver with portal venous blood before also entering by the hepatic veins
• The remainder is bypassed into the inferior vena cava by the venous duct.

Blood from the venous duct and hepatic veins mixes in the inferior vena cava with blood from the lower limbs and abdominal wall. It enters the right atrium and, guided by the valve of the inferior vena cava, passes mostly through the oval foramen into the left atrium, where it mingles with the limited venous return from the pulmonary veins. Some blood returning via the inferior vena cava, instead of traversing the oval foramen, joins blood from the superior vena cava and passes through the right atrium to reach the right ventricle. From the left atrium, blood enters the left ventricle and thence the aorta, by which it is probably distributed almost entirely to the heart, head and upper limbs, little reaching the descending aorta. Blood from the head and upper limbs returns via the superior vena cava to the right atrium, all of which traverses the right atrioventricular orifice, along with the small amount returned via the inferior vena cava. From the right ventricle, this blood enters the pulmonary trunk. The fetal lungs are largely inactive, so only a little of the blood from the right ventricle traverses the right and left pulmonary arteries, and this returns by the pulmonary veins to the left atrium. The greater part of the outflow through the pulmonary trunk is carried by the *arterial duct* (*ductus arteriosus*) directly to the aorta, where it mixes with the small quantity of blood passed from the left ventricle into this part of the aorta. The mixture descends

150

the aorta and is partly distributed to the lower limbs and the organs of the abdomen and pelvis. Most is returned via the umbilical arteries to the placenta.

In terms of function, it is the placenta which serves as the organ for fetal nutrition and excretion, receiving deoxygenated fetal blood and returning it oxygenated and detoxified. Most of the blood entering the left atrium comes from the right atrium, right atrial pressure being much higher than that in the left atrium. Hence, the flap-like valve of the primary septum (p. 304) is thrust to the left (3.168, 169, 170), allowing passage of blood from the right to the left atrium. The valve of the inferior vena cava is so placed as to direct nearly all the richly oxygenated blood from the umbilical vein to the oval foramen and left atrium, whereas most of the venous blood from the superior vena cava enters the right ventricle directly through the right atrioventricular orifice. The refreshed placental blood, therefore, mixed with blood from the portal vein and inferior vena cava, passes almost directly to the aorta for distribution to the head and upper limbs. In contrast, the blood which reaches the descending aorta through the ductus arteriosus is mostly the blood which has circulated through the head and upper limbs, with only a small amount coming from the pulmonary veins and left atrium. This blood is distributed to the abdomen and lower limbs, but principally returns to the placenta.

SYSTEM

At birth, as pulmonary respiration begins, increased amounts of blood from the pulmonary trunk traverse the pulmonary arteries to the lungs and return by the pulmonary veins to the left atrium. Consequently, pressure rises within the left atrium. A fall in pressure also occurs in the inferior vena cava due to reduction of venous return concomitant with occlusion of the umbilical vein and venous duct. Atrial pressures become equal and the valvar oval foramen is closed by apposition, and later fusion, of the primary septum to the rims of the foramen (p. 304). Contraction of the atrial septal muscle, synchronized with that in the superior vena cava, may assist this closure which occurs after functional closure of the ductus arteriosus. Sometimes fusion is incomplete, a potential atrial communication persisting throughout life. Almost always this has no functional effect, since the inequality of atrial pressures and the valve-like arrangement of the opening do not favour passage of blood. When the umbilical cord is ligated, arresting placental circulation, the umbilical vein thromboses, gradually becoming the ligamentum teres. Umbilical vessels are muscular but devoid of a nerve supply in their extra-abdominal course. They constrict in response to handling, stretching, cooling and altered tensions of oxygen and carbon dioxide. The venous duct (*ductus venosus*) shuts down by an unknown mechanism. It is already closed in about one-third of newborn infants (Rudolph et al 1961). Its fibrous remnant is the venous ligament (*ligamentum venosum*). After ligation of the umbilical cord, the umbilical (hypogastric) arteries also thrombose from the origin of their last branches (superior vesical arteries) to the umbilicus, subsequently becoming fibrous chordae (medial umbilical ligaments) in the extraperitoneal fat of the abdominal wall.

The ductus arteriosus contracts rapidly immediately after birth, although blood probably continues to flow intermittently through it for a week or so. Such flow, nonetheless, is reversed relative to that occurring in the fetal circulation. This is the consequence of the rise in systemic vascular resistance which results from exclusion of the placental circulation, and the fall in pulmonary resistance occurring with expansion of the lungs. Anatomic closure of the duct is due to endothelial proliferation but takes some months to complete. Initial constriction at birth has been attributed to raised oxygen tension. A neural factor may also be involved, the muscular wall having afferent and efferent nerve endings and responding to adrenaline and nor-adrenaline (Franklin 1939; Barcroft 1941; Barclay et al 1942). After closure, the duct becomes an impervious ligament connecting the left pulmonary artery (near its origin) with the aortic arch. (For morphological and biomechanical studies of the arterial ligament, consult Dohr et al 1986. For a general review of perinatal vascular changes, see Dawes 1969.)

Congenital malformations of the heart are relatively common, amounting to about one-quarter of all developmental abnormalities. Their incidence is estimated at 8 per 1000 live births, but they are found in up to 2% of stillbirths. Only a small proportion of the anomalies are directly attributable to genetic or environmental factors, the majority being the result of multifactorial events.

ABNORMALITIES OF THE CARDIAC POSITION

The most severe abnormality of position is an extrathoracic heart, so-called *ectopia cordis*. The heart usually projects to the surface through the lower thoracic and upper abdominal wall, remaining covered in most instances by the fibrous pericardium. There is usually additional herniation of the abdominal contents. Another abnormality of position is for the heart to show a mirror-like reversal in shape and position, being found in the right hemithorax with its apex directed to the right instead of the left (*dextrocardia*). This arrangement may be part of a general mirror-like reversal (so-called general '*situs inversus*'). More usually an abnormal location of the heart is found with an arrangement known as *isomerism*, in which both sides of the thorax, including the atrial appendages, retain features of either morphological rightness or leftness. This is also usually associated with anomalous arrangement of the abdominal organs, *right isomerism* associated with absence of the spleen (*asplenia*) and left isomerism with multiple spleens (*polysplenia*). The heart can also be abnormally located when the rest of the body is normal. Such an abnormal location usually indicates presence of additional lesions within the heart but can simply be the consequence of abnormality of the lungs, the abnormally located heart being anatomically normal.

DEFECTS OF THE CARDIAC SEPTATION

Most anomalies can be placed in this group, with simple deficiencies of septation affecting the atrial septum, the atrioventricular septum, the ventricular septum or the arterial pole of the developing heart. More complex forms with abnormal septation represent failure of, or inappropriate, connection of the atria to the ventricles. In this set can be placed anomalies such as double inlet ventricle; absence of one atrioventricular connection (tricuspid or mitral atresia); and discordant atrioventricular connections (congenitally corrected transposition).

Atrial septal defects

Defects within the oval fossa. A persistent communication between the atrial chambers within the oval fossa is common, resulting from failure of fusion of the primary atrial septum (the flap valve) with the infolded muscular rims of the fossa. When the flap valve is still able to overlap the rims, the communication is of no functional significance as long as left atrial pressure is higher than right, which is usually the case. In contrast, when the flap valve is smaller than the fossa, or when it is perforate, there is a true atrial septal defect (10.61).

Other atrial communications. In normal development, the free edge of the primary septum fuses with the atrioventricular endocardial cushions, permitting subsequent formation of the atrioventricular septum. When this process fails to occur, the entire atrioventricular junction is malformed, with an atrioventricular septal defect being part of the complex anomaly. This defect can be found when the leaflets of the atrioventricular valves are fused to the crest of the ventricular septum (10.62), producing an interatrial communication at the expected site of the atrioventricular septum. This so-called '*ostium primum*' defect, therefore, is properly classed as an atrioventricular septal defect (see below). Other interatrial communications can be formed in the mouths of the venae cavae, most frequently the superior vena cava, and are usually associated with drainage of the right pulmonary veins into the cavo-atrial junction. Known as *sinus venosus defects* (10.61), their essential feature is a bi-atrial connection of the vena cava. An interatrial

communication can also occur through the mouth of the coronary sinus when there is a deficiency or absence of the wall usually separating the sinus from the left atrium.

Atrioventricular septal defects

Atrioventricular septal defects result from failure of fusion of the endocardial atrioventricular cushions, leaving a common atrioventricular orifice and deficiencies of the adjacent septal structures (10.62). The common orifice is guarded by a basically common valve, with superior and inferior leaflets bridging the scooped-out ventricular septum to be tethered in both right and left ventricles. Although the left component of the valve thus formed is often interpreted as a 'cleft mitral valve', in reality it bears no resemblance to the normally structured mitral valve, having three leaflets and with the 'cleft' forming the zone of apposition between the left ventricular components of the bridging leaflets. The defects show marked variation according to the attachments of the bridging leaflets of the common valve to each other and to the adjacent atrial and ventricular septal structures. Two major subgroups are identified. The more frequent pattern has a common atrioventricular orifice and the potential for shunting through the septal defect at both atrial and ventricular levels (10.62, middle). The minority of cases have separate right and left atrioventricular orifices with shunting possible only at atrial level. Although the latter defect is often described as an *ostium primum atrial septal defect*, it is, in reality, an atrioventricular septal defect.

Ventricular septal defects

The commonest defect of the ventricular septum is found in the environs of the expected site of the membranous septum in the right wall of the aortic vestibule, below the commissure between the non-coronary and right coronary leaflets of the aortic valve (10.63). The defect is closely related to the septal leaflet of the tricuspid valve, but can extend to open into the ventricular outlet beneath the supraventricular crest (p. 1480). It results from incomplete closure of the ventricular septum by its membranous component, often being associated with overriding of the crest of the muscular septum by the aortic orifice, along with pulmonary stenosis or atresia and hypertrophy of the right ventricle (*Fallot's tetralogy*). Rarely the pulmonary trunk can be normal or even dilated with this combination, giving the so-called *Eisenmenger complex*. Such perimembranous defects, so called because they have the remnant of the membranous septum as part of their perimeter, can also be found with abnormal ventriculo-arterial connections (see below). It is then often the pulmonary trunk which overrides the muscular septum, giving the so-called *Taussig–Bing syndrome*. In perimembranous ventricular septal defects, the atrioventricular bundle and its right and left branches are always found along the *postero-inferior margin* of the defect (Latham & Anderson 1972).

Less commonly, a septal defect can be found in the ventricular outflow tracts roofed by the conjoined facing leaflets of the aortic and pulmonary valves. Such juxta-arterial defects are doubly committed in that they open beneath the orifices of both aortic and pulmonary valves. They are due to failure of formation of both the outlet component of the muscular ventricular septum and the free-standing subpulmonary muscular infundibulum, but with appropriate septation at the ventriculo-arterial junction. They usually have a muscular postero-inferior rim which protects the atrioventricular bundle, but can extend to become perimembranous.

The third type of ventricular septal defect is made up of those enclosed within the musculature of the septum. Such muscular defects can occur in all parts of the septum, and can be multiple, producing a so-called 'Swiss-Cheese' septum.

Defects within the inlet part of the septum are important because the atrioventricular bundle passes in their upper border, in contrast to perimembranous defects opening to the inlet of the right ventricle where the atrioventricular bundle is postero-inferiorly located.

Common arterial trunk

The essence of a common arterial trunk lesion is presence of an undivided arterial channel, guarded by a common arterial valve, positioned above and astride the free margin of the muscular ventricular septum (10.64). There is, therefore, a coexisting juxta-arterial deficiency of the ventricular septum. The right and left pulmonary arteries usually arise via a confluent segment but can take independent origin from the common arterial trunk, which continues as the ascending aorta. The common valve usually has three leaflets, but may have two, four, or more. The lesion is due to a failure of development of the aorticopulmonary septum, and is almost certainly linked to abnormal migration of cells into the heart from the neural crest.

ABNORMAL CONNECTIONS OF THE GREAT ARTERIES AND VEINS

Complete transposition is the condition in which the aorta arises from the right ventricle and the pulmonary trunk from the left. Better described as showing discordant ventriculo-arterial connections, such hearts can coexist with deficiencies of cardiac septation. They can also be found with discordant connections at the atrioventricular junction (congenitally corrected transposition). The developmental history of the discordant connections is still unknown.

Double outlet ventricle exists when the greater part of both arterial valves are attached within the same ventricle, almost always the right. For circulation to continue, it is then necessary for the ventricular septum to be deficient, although the septal defect can rarely close as a secondary event. The position of the septal defect serves for subclassification. It is usually beneath the aorta or the pulmonary trunk, but can be doubly committed or even non-committed.

Either the systemic or pulmonary veins can be anomalously connected. The commonest systemic anomaly is found when a persistent left superior vena cava drains into the right atrium through the enlarged orifice of the coronary sinus.

More rarely, the left vena cava may connect directly with the superior aspect of the left atrium, usually associated with unroofing of the coronary sinus, the orifice of the sinus then functioning as an interatrial communication. The commonest lesion of the inferior vena cava is for its abdominal course to be interrupted, with drainage to the heart via the azygos or hemiazygos venous system. This lesion is found most frequently with left isomerism.

The pulmonary veins can be connected to an anomalous site individually or in combination. Totally anomalous connection is of most significance. Usually the veins form a confluence behind the left atrium which then connects either to the superior vena cava, to the coronary sinus, or to the portal venous system having traversed the diaphragm.

A right aortic arch is found most frequently with tetralogy of Fallot or with common arterial trunk. It can also exist, together with a left arch, in various combinations known as arterial rings which compress the oesophagus, giving so-called dysphagia lusoria. Persistent patency of the ductus arteriosus (p. 1052) must be distinguished from delayed closure. The persistently patent duct can be an obligatory part of the circulation when associated with aortic or pulmonary atresia. Coarctation of the aorta can be found as an isolated lesion when the ductus arteriosus is closed, or with an open duct when it is more likely to be associated with additional lesions within the heart. Congenital cardiac malformations are often multiple and probably occur more frequently in siblings and in children of consanguineous marriages. There is a low correlation, however, among monozygotic twins. Ventricular septal defects are the commonest lesions, making up about 20% of all cases. This is followed by persistent patency of the ductus arteriosus, coarctation, pulmonary stenosis, Fallot's tetralogy, complete transposition, aortic stenosis, and hypoplastic left heart syndrome, each of these accounting for between 5% and 10% of all cases.

PULMONARY TRUNK

The pulmonary trunk, or pulmonary artery (10.65, 66, 68) conveys deoxygenated blood from the right ventricle to the lungs. About 5 cm in length and 3 cm in diameter, it is the most anterior of the cardiac vessels and it arises from the base of the right ventricle (from the pulmonary annulus surmounting the conus arteriosus) above and to the left of the supraventricular crest. It slopes up and back, at first in front of the ascending aorta, then to its left. Below the aortic arch it divides, level with the fifth thoracic vertebra and to the left of the midline, into the right and left pulmonary arteries of almost equal size. Thus the pulmonary trunk bifurcation lies **below, in front** and to the **left** of the tracheal bifurcation, which is also associated with the inferior tracheobronchial lymph nodes and the deep cardiac nerve plexus. In the fetus the pulmonary artery at the level of the bifurcation is connected to the aortic arch by the ductus arteriosus, which lies in the same direction as the pulmonary artery.

Relations

The artery is entirely within the pericardium, enclosed with the ascending aorta in a common tube of visceral pericardium; the fibrous pericardium gradually peters out in the adventitia of the pulmonary arteries. **Anteriorly** it is separated from the sternal end of the left second intercostal space by the pleura, left lung and pericardium. **Posterior** are at first the ascending aorta and left coronary artery, then the left atrium. The ascending aorta is finally on its right. An auricle and coronary artery are on each side of its origin. The superficial cardiac plexus is between the pulmonary bifurcation and the aortic arch; above, behind and right are the tracheal bifurcation, lymph nodes and nerves (see above).
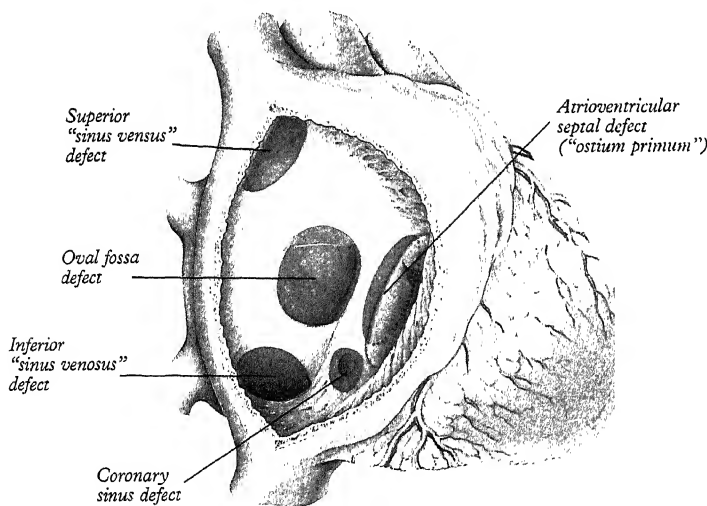
During fetal life, when blood pressure is similar in the pulmonary artery and the aorta, the structure of the vessels is similar. After birth, with the expansion of the lungs and dilatation of pulmonary arterioles, pulmonary vascular resistance falls while blood flow increases; the systolic pressure in the pulmonary artery falls and this is accompanied by a structural remodelling of the wall. The elastic material, which has originally a lamellar structure, becomes aggregated into star-shaped units which are linked to many muscle cells. The amount of musculature grows extensively after birth and it exceeds that found in the aorta; in the latter, however, the thickness of the wall is about twice that in the pulmonary artery.

Right pulmonary artery. Slightly longer and larger than the left artery, it runs horizontally to the right, behind the ascending aorta, superior vena cava and upper right pulmonary vein, then in front and below the tracheal bifurcation (see above) and thence in front of the oesophagus and right main bronchus to the right pulmonary hilum. It divides as it emerges from behind the superior vena cava into two large branches. A lymph node usually occupies the bifurcation. The superior branch, which is the smaller of the two, goes to the superior lobe and it usually divides into two further branches which supply the majority of that lobe. The inferior branch descends anterior to the intermediate bronchus and immediately posterior to the superior pulmonary vein. It gives off a small recurrent branch to the superior lobe and, at the point where the horizontal fissure meets the oblique fissure, this branch of the pulmonary artery then gives off anteriorly the branch to the middle lobe and posteriorly the branch to the superior segment of the inferior lobe. It then continues a short distance before dividing to supply the rest of the inferior lobe segments.

Left pulmonary artery. Shorter and smaller than the right, it runs horizontally in front of the ascending aorta and the left principal bronchus to the left hilum. It emerges from within the concavity of the aortic arch and descends anterior to the descending aorta to enter the oblique fissure. The branches of the left pulmonary artery are extremely variable. Usually its first and largest branch is to the anterior segment of the left superior lobe. Prior to reaching the fissure it gives off a variable number of other branches to the superior lobe. As it enters the fissure it usually supplies a large branch to the superior segment of the inferior lobe. Lingular branches arise within the fissure and the rest of the lower lobe is supplied by many varied branching patterns. It was a surgical aphorism of the late Lord Brock that when performing a left upper lobectomy 'There was always one more branch of the pulmonary artery than you thought!'.

Superior
"sinus vensus"
defect

Atrioventricular
septal defect
("ostium primum")

Oval fossa
defect

Inferior
"sinus venosus"
defect

Coronary
sinus defect

10.61 This drawing shows the location of the defects which produce an interatrial communication. Only defects within the oval fossa are true atrial septal defects.
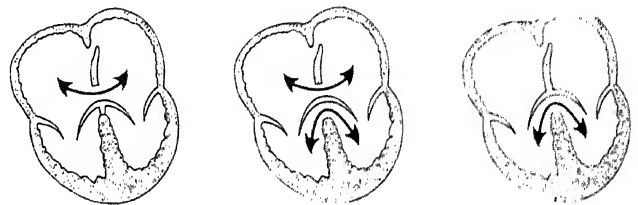
10.62 This drawing shows how, depending on the attachment of the bridging leaflets, shunting across an atrioventricular septal defect can be atrial, ventricular or both levels.

AORTA

The aorta, the trunk of the arterial tree conveying oxygenated blood to the body, begins at the aortic annulus (pp. 1488, 1493), part of the base of the left ventricle, where it is about 3 cm in diameter. Passing up and right for about 5 cm, it arches upwards, backwards and to the left over the left pulmonary hilum and then descends in the thorax at first left of the vertebral column, then gradually inclining towards the midline, to enter the abdomen via the diaphragm's aortic hiatus. Diminished in size to about 1.75 cm, it ends a little left of

the midline, level with the lower border of the fourth lumbar vertebra, dividing into the right and left common iliac arteries. For convenience it is described as arbitrarily divided into *ascending, arch* and *descending thoracic* and *abdominal* parts.

The ascending aorta (**10.23A**, **26**, **65**, **66**, **67**), about 5 cm long, begins at the base of the left ventricle, level with the third left costal cartilage's lower border; it ascends obliquely, curving forwards and right, behind the left half of the sternum to the level of the second left costal cartilage's upper border. At its origin, close to the aortic annulus, the sectional profile is larger and not circular because of three almost hemispherical outward bulges (sinuses of Valsalva), one posterior (non-coronary), one left and one right, which correspond to the three cusps of the aortic valve (p. 1488). Distal to the aortic annulus are three aortic sinuses, beyond which the vessel's calibre is slightly increased by a bulging of its right wall; this aortic bulb gives the vessel an oval section.

Relations

The ascending aorta is within the fibrous pericardium, enclosed in a tube of serosal pericardium with the pulmonary trunk (**10.19**). Anterior to its lower part are the infundibulum (p. 1480), the initial segment of the pulmonary trunk, and the right auricle; superiorly, it is separated from the sternum by the pericardium, right pleura, anterior margin of the right lung, loose areolar tissue and thymic remains; posterior are the left atrium, right pulmonary artery and principal bronchus; right lateral are the superior vena cava and right atrium, the former partly posterior; left lateral are the left atrium and, at a higher level, the pulmonary trunk.

At least two structures (reminiscent of the carotid arterial chemoreceptors and baroreceptors, p. 971) lie between the ascending aorta and the pulmonary trunk. The inferior aorticopulmonary body is near the heart and anterior to the aorta; the middle aorticopulmonary body is near the right side of the ascending aorta (Boyd 1961).

Branches form the right and left coronary arteries (**10.67A–E**), supplying the heart itself.

CORONARY ARTERIES

The right and left coronary arteries issue from the ascending aorta in its anterior and left posterior sinuses (**10.65**, **67A–E**). Variations are rare but the two may start, separately or in common, from the same sinus; three or even four coronary arteries have been observed; the most common variation concerns a right coronary branch, *arteria coni arteriosi* or 'conus artery', which is usually (64%) its first branch but often arises separately in the anterior sinus (36%), as a third coronary artery. The left coronary opening may be double, leading into major initial branches, usually the circumflex and anterior interventricular; one may lead into a stem common to one such branch and a diagonal ventricular ramus. The levels of coronary orifices are variable; Thebesius (1708) appears to have started a view that aortic cusps obstruct them when fully spread in systole; but the coronary orifices are at a higher level, at or above cuspal margins, though below in about 10% (right coronary) and 15% (left). (Further, as detailed on p. 1486 et seq, it is now established that, even at the

Doubly committed juxta-arterial defects
* *Beneath aortic and pulmonary valves*

Can extend to become perimembranous

Muscular defects
* *entirely enclosed in muscular septum*

* *can occur between inlet, apical trabecular or outlet ventricular*

Perimembranous defects

* *Abut on central fibrous body*

* *can extend to open between inlet, apical trabecular or outlet trabecular components, or can be confluent*

10.63 Diagram showing how, based on the structure of the anatomic borders seen from the right ventricle, ventricular septal defects can be placed into perimembranous, muscular or doubly committed groups.

10.64 This heart possesses a common arterial trunk, with a common truncal valve overriding a juxta-arterial deficiency of the ventricular septum. It is due to failure of septation of the arterial pole of the developing heart. (Specimen prepared by Dr Leon M Gerlis.)

Pulmonary trunk
Wire in transverse sinus
Left phrenic nerve
Left pulmonary artery
Left principal bronchus
Left vagus nerve
Thoracic duct
Descending thoracic aorta

Wire in transverse sinus
Ascending aorta
Superior vena cava
Right phrenic nerve
Right pulmonary artery
Lymph nodes
Right principal bronchus
Right vagus nerve
Oesophagus
Pleural recess
Vena azygos
Fifth thoracic vertebra

10.65 Transverse section through the mediastinum at the level of the upper border of the fifth thoracic vertebra: superior aspect. Note nerve fibres of the deep cardiac and posterior pulmonary plexuses, inferior tracheobronchial and hilar lymph nodes.

Right common carotid artery
Inferior thyroid vein
Recurrent laryngeal nerve
Trachea
Left common carotid artery
Left vagus nerve
Left internal jugular vein
Right internal jugular vein
External jugular vein
Left subclavian artery
Right subclavian artery
Left subclavian vein
Right subclavian vein
Left internal thoracic vessels
Right brachiocephalic vein
Left superior intercostal vein
Right internal thoracic vessels
Left vagus nerve
Thymic vein
Ligamentum arteriosum
Right vagus nerve
Recurrent laryngeal nerve
Aorta
Left pulmonary artery
Azygos vein
Cardiac branches of right vagus nerve
Superior pulmonary vein
Right principal bronchus
Cardiac branch
Right pulmonary artery
Left principal bronchus
Superior pulmonary vein
Left atrium and auricle
Superior vena cava
Pulmonary trunk
Aorta
Infundibulum (conus)
Right phrenic nerve
Right ventricle
Right atrium and its auricle
Left phrenic nerve
Anterior interventricular branch of left coronary artery and great cardiac vein
Right coronary artery and small cardiac vein
Left ventricle
Cardiac apex

10.66 The relations of the pulmonary arteries and primary bronchi seen from the front. Parts of the ascending aorta, pulmonary trunk and superior vena cava have been removed in the dissection. The right vagal trunk is uncoloured to avoid confusion.

height of the systole, the cusps do not 'flatten' against, i.e. co-apt to, the walls of their sinuses.)

The two arteries, as indicated by their name, form an oblique inverted crown, with an anastomotic circle in the atrioventricular sulcus connected by marginal and interventricular loops intersecting at the cardiac apex (10.67A–E). This is, of course, only an approximation; the degree of anastomosis is most variable and usually insignificant (see below). The main arteries and major rami are usually subepicardial but those in the atrioventricular and interventricular sulci are often deeply sited, occasionally hidden by overlapping myocardium or embedded in it. Myocardial strands may also cross atrial or ventricular branches; Poláček (1961) found them in more than 80% of ventricles; Bloor and Lowman (1963) have emphasized their importance in interpretation of coronary arteriograms.

The term 'dominant' is used to refer to the coronary artery which gives the posterior interventricular branch, supplying the posterior part of the ventricular septum and often part of the posterolateral wall of the left ventricle. In 70% of people this is the left coronary artery, which is also invariably the larger of the two vessels. In the remaining cases the posterior interventricular branch is either bilateral, issuing from both the right coronary artery and the left circumflex artery, or absent and replaced by a network of smaller vessels from both right and left coronaries. Anastomoses between right and left coronary arteries are abundant during fetal life but are much reduced by the end of the first year of life. Anastomoses providing collateral circulation may become prominent in conditions of hypoxia and in coronary artery diseases. An additional collateral circulation is provided by small branches from mediastinal, pericardial and bronchial vessels.

The diameters of coronary arteries, both main stems and larger branches, have often been recorded; such figures are of limited value, since technique is not always stated, physiological state often ignored and measurement of external or internal diameters not clearly distinguished. Calibre is usually the basis, most measurements being made on arterial casts or angiograms. The maximum ranges recorded in major studies are 1.5–5.5 mm for coronary arteries at their origins. Baroldi and Scomazzoni (1967) give means of 4.0 and 3.2 mm. The left exceed the right in about 60% of hearts, the right being larger in 17%, the vessels approximately equal in 23%. Vogelberg (1957) considered that coronary diameters increase up to the thirtieth year.

Right coronary artery

Arising from the anterior ('right coronary') aortic sinus, the artery passes at first anteriorly and slightly to the right between the right auricle and pulmonary trunk, where the sinus usually bulges. Reaching the atrioventricular (coronary) sulcus it descends in this almost vertically to the right (acute) cardiac border, curving around it into the posterior part of the sulcus, where it approaches its junction with both interatrial and interventricular grooves, a region appropriately termed the *crux of the heart*. In about 60% of subjects the artery reaches the crux and ends a little left of it by variable anastomosis with circumflex branch of the left coronary. In a minority, the right coronary artery ends near the right cardiac border (c. 10%) or between this and the crux (c. 10%); more often (c. 20%) it reaches the left border, replacing part of the circumflex artery.

Branches of the right coronary supply both right atrium and ventricle and, variably, parts of the **left** chambers and atrioventricular septum. The first branch (arising separately from the anterior aortic sinus in 36% of cases) is the *conus artery* (sometimes a 'third coronary'); since a similar vessel comes from the left coronary, this is more correctly named the *right conus artery*. It ramifies anteriorly on the lowest part of the pulmonary conus and upper part of right ventricle; it commonly anastomoses with a similar left coronary branch to form the '*annulus of Vieussens*', a tenuous anastomotic 'circle' around the pulmonary trunk. Descriptions of the conus artery vary (Baroldi & Scomazzoni 1967), some regarding the right conus artery of significance in coronary arterial disease; some consider it to be the right coronary's first ventricular branch, supplying a variable region from the conus to the apex.

Anterior atrial and ventricular rami diverge from the so-called *first segment of the right coronary*, extending from its origin to the right margin of the heart. Both groups diverge widely, approaching

a right angle in the case of ventricular arteries, in contrast to the more acute origins of the left coronary ventricular rami. The *right anterior ventricular rami*, usually two or three, ramify towards the cardiac apex, which they rarely reach unless the right marginal branch is included, as it is by some; this is then the largest right anterior ventricular ramus, greater in calibre and long enough to reach the apex in most hearts (93%; Baroldi & Scomazzoni 1967). When the right marginal artery is very large, the remaining anterior ventricular rami may be reduced to one, or may be absent. From the *second segment of the right coronary artery* (between the right border and crux) one to three small *right posterior ventricular rami*, commonly two, supply the diaphragmatic aspect of the right ventricle. Their size is inversely proportional to that of the right marginal artery, as in the anterior right ventricular supply, the right marginal usually extending to the cardiac diaphragmatic surface. Posterior right ventricular rami may be absent. As the right coronary approaches the crux, it produces one to three posterior interventricular rami but only one in the interventricular sulcus; this *posterior interventricular artery*, single in about 70%, is otherwise accompanied by parallel right coronary branches, to the right or left or on both sides of the sulcus. When these flanking vessels exist, branches of the posterior (descending) interventricular artery are small and sparse; when it exists alone it gives off a few branches, particularly to the right ventricle but also to the left. It is replaced in about 10% of cases by a left coronary branch.

The atrial rami of the right coronary artery are sometimes described as anterior, lateral (right or marginal) and posterior groups but are most frequently single, small vessels averaging 1 mm in diameter. The right anterior and lateral are occasionally double, very rarely triple, and supply chiefly the right atrium. The posterior ramus is usually single, distributed to the right and left atria; but in 40% or more a left posterior atrial branch of the right coronary exists. The artery of the sinuatrial node is an atrial branch, distributed largely to the myocardium of both atria, mainly the right. Its origin is variable: from the left coronary in about 35% (Hutchinson 1978), arising from its circumflex branch (see below); when it is a branch of the right coronary, it usually comes from its anterior stem, less often from its right lateral part, least often from its posterior atrioventricular part. This 'nodal' artery thus usually passes back in the sulcus between the right auricular appendage and aorta. Whatever its origin the artery usually branches around the superior vena cava's base, commonly as an arterial loop from which small rami supply the right atrium. A large '*ramus cristae terminalis*' (Spalteholtz 1924) traverses the sinuatrial node (10.67A–C); perhaps instead this ramus should be termed 'nodal artery', since most of the currently named vessel actually supplies the atria and is more appropriately named the 'main atrial branch' (Baroldi & Scomazzoni 1967).

Right coronary septal rami are relatively short, leaving its posterior interventricular ramus to supply the posterior interventricular septum. They are numerous but do not usually reach the apical septal parts (supplied by terminal septal branches of the anterior interventricular).

The largest posterior septal artery, usually the first, is commonly from the inverted loop said to characterize the right coronary artery at the crux, where its posterior interventricular branch arises; this large posterior septal artery usually supplies the atrioventricular node—in 80% of hearts, according to Hutchinson (1978).

DiDio et al (1967) described the atrioventricular rami of the right coronary artery as consisting of small recurrent branches from each ventricular artery crossing the atrioventricular sulcus to supply the adjoining atrial myocardium, or ventricular twigs from the atrial arteries.

Left coronary artery

The left coronary artery is the larger in calibre, supplying a greater volume of myocardium, including almost all the left ventricle and atrium, except in so-called 'right dominance' where the right coronary partly supplies a posterior region of the left ventricle (10.67A–C). The left coronary usually supplies most of the interventricular septum. Its initial stem, between its ostium in the left posterior ('left coronary') aortic sinus and its first branches, varies in length from a few millimetres to a few centimetres. It lies between the pulmonary trunk and the left auricular appendage, emerging into the atrioventricular sulcus, in which it turns left; this part is loosely embedded in **150**

Arch of aorta

Superior vena cava

Sinuatrial nodal artery

Right coronary artery

Outlines of:
Anterior aortic sinus
Right posterior aortic sinus
Left posterior aortic sinus

Right conus artery

Right anterior ventricular arteries

Atrioventricular nodal artery

Posterior interventricular arteries

Right (acute) marginal artery

Pulmonary trunk
Left coronary artery (main stem)
Left auricular appendage
Left atrial rami

Left conus artery
Circumflex artery
Left (obtuse) marginal artery

Diagonal artery

Anterior interventricular artery
Interventricular anterior septal rami

B

Sinuatrial artery

C

10.67A–C   Anterior views of the coronary arterial system, with the principal variations.
A   The commonest arrangement.
B   A common variation in the origin of the sinuatrial nodal artery.
C   An example of left 'dominance' by the left coronary artery, showing also an uncommon origin of the sinuatrial artery.
Note that in 10.67A–E the right coronary arterial tree is shown in magenta, the left in full red. In both cases posterior distribution is shown in a paler shade.

1508

Ascending aorta

Pulmonary trunk

Superior vena cava

Left pulmonary veins

Right pulmonary veins

Stem of posterior atrial arteries

Circumflex artery

Region of crux of heart

Right posterior atrial arteries

Inferior vena cava

Anterior interventricular artery (termination)

Right coronary artery

Posterior interventricular arteries

E

10.67D, E Postero-inferior views of the coronary arterial system.
D An example of the more normal distribution in right 'dominance'.
E A less common form of left 'dominance'.
N.B. In these 'posterior' views the diaphragmatic (inferior) surface of the ventricular part of the heart has been artificially displaced and foreshortening ignored to clarify the details of the so-called posterior (inferior) distribution of the coronary arteries.

subepicardial fat and usually has no branches; but a small atrial ramus may occur and, rarely, the sinuatrial nodal artery may arise from the left coronary artery (James 1961); but when it is a ramus of the left coronary it almost always comes from the circumflex branch. Reaching the atrioventricular or coronary sulcus, the left coron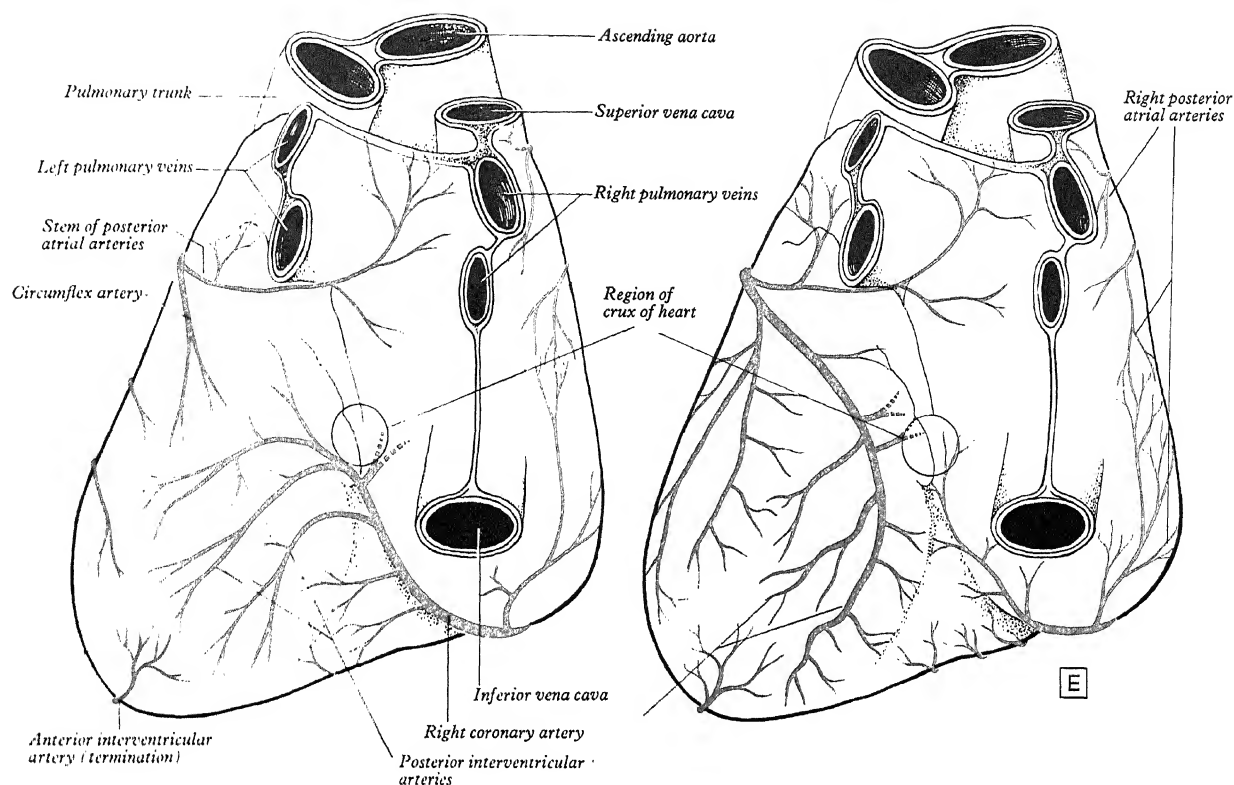ary divides into two or three main rami, its *anterior interventricular* (*descending*) *ramus* being commonly described as its continuation; this descends obliquely forward and left in the interventricular sulcus, sometimes deeply embedded or crossed by bridges of myocardial tissue and by the great cardiac vein and its tributaries. It reaches the apex almost always, terminating there in one-third of specimens, but more often turning round the apex into the posterior interventricular sulcus, in which it traverses a third to a half of its length, to meet the terminal twigs of the corresponding right coronary ramus.

The *anterior interventricular artery* produces right and left anterior ventricular, anterior septal and variable, corresponding posterior rami. Right anterior ventricular rami are small and rarely number more than one or two, the right ventricle being supplied almost wholly by the right coronary artery.

From two to nine large left *anterior ventricular arteries* branch at acute angles from the anterior interventricular to cross diagonally the left ventricle's anterior aspect, larger terminals reaching the rounded (obtuse) left border. One is often large and may arise separately from the left coronary trunk (which then ends by trifurcation); this left diagonal artery, reported in 33–50% or more cases, is occasionally duplicated (20%). A small left conus artery frequently leaves the anterior interventricular near its start, anastomosing on the conus with that of the right coronary and with the vasa vasorum of the pulmonary artery and aorta. The anterior septal rami leave the anterior interventricular almost perpendicularly, passing back and down in the septum, of which they usually supply about the ventral two-thirds. Small posterior septal rami from the same source supply the posterior septal third for a variable distance from the cardiac apex.

The *circumflex artery*, in calibre comparable to the anterior interventricular, curves left in the atrioventricular sulcus, continuing round the left cardiac border into the posterior part of the sulcus and ending left of the crux in most hearts, but sometimes continuing as a posterior interventricular artery. Proximally the left auricular appendage usually overlaps it. In about 90% a large ventricular branch, the *left marginal artery*, arises perpendicularly from it to ramify over the rounded 'obtuse' margin, supplying much of the adjacent left ventricle, usually to the apex. Smaller anterior and posterior rami of the circumflex artery also supply the left ventricle. *Anterior ventricular branches* (1–5, commonly 2 or 3) course parallel to the diagonal artery, when present, replacing it when absent. *Posterior ventricular branches* are smaller and fewer, the left ventricle being partly supplied by the posterior interventricular artery; when this is small or absent, it is accompanied or replaced by an interventricular continuation of the circumflex. Such a *left posterior interventricular artery* is frequently double or triple. Atrial rami, anterior, lateral and posterior, from the circumflex, supply the left atrium.

Inconstant branches of the circumflex artery require mention. The *artery to the sinuatrial node* is a branch in about 35% (Hutchinson 1978), usually from the anterior circumflex segment, less often the circummarginal. It passes over and supplies the left atrium, encircling the superior vena cava like a right coronary nodal ramus. It sends a large branch to (and through) the node but is predominantly atrial in distribution. The artery to the atrioventricular node, the terminal ramus in 20%, arises near the crux and then the circumflex usually supplies a posterior interventricular ramus, an example of so-called 'left dominance' (see below). *Kugel's anastomotic artery*, 'arteria anastomotica auricularis magna,' was described by Kugel (1927) as a constant circumflex branch, usually from its anterior part, traversing the interatrial septum (near its ventricular border) to establish direct or indirect anastomosis with the right coronary. This anastomosis is controversial, apparently accepted by James (1978) but denied

150

by Baroldi and Scomazzoni (1967). James considered it an auxiliary supply to the atrioventricular node.

Details of coronary distribution require integration into a concept of total cardiac supply. Most commonly the right coronary supplies all the right ventricle (except a small region right of the anterior interventricular sulcus), a variable part of the left ventricular diaphragmatic aspect, the postero-inferior third of the intraventricular septum, the right atrium and part of the left, and the conducting system as far as the proximal parts of the right and left crura. Left coronary distribution is, of course, reciprocal, including most of the left ventricle (see above), a narrow strip of right ventricle (see below), the anterior two-thirds of the interventricular septum and most of the left atrium. As noted, variations (10.67A–E) chiefly affect the diaphragmatic aspect of ventricles residing in relative 'dominance' of supply by the left or right coronary artery. The term is misleading, since the left artery almost always supplies a greater volume of tissue. In 'right dominance' the posterior interventricular artery is from the right coronary, in 'left dominance' from the left. In the so-called 'balanced' pattern, branches of both run in or near the sulcus. Less is known of variation in atrial supply; the small vessels involved are not easily preserved in corrosion casts. From Hutchinson's results (1978) it is apparent that in over 50% the right atrium is supplied only by the right coronary, the rest receiving a dual supply. More than 62% of left atria are largely supplied by the left and about 27% by the right coronary; but in each group a small accessory supply from the other coronary exists, 11% being supplied almost equally by both. Sinuatrial and atrioventricular supplies also vary. According to James (1961) right and left coronary arteries supply the sinuatrial node respectively in 55% and 45%, corresponding values from Baroldi and Scomazzoni's study (1967) being 51% and 41% (8% receiving bilateral supply), and from Hutchinson (1978) 65% and 35%. For the atrioventricular node James's values are 90% (right coronary) and 10% (left coronary), Hutchinson's 80% and 20% respectively; Baroldi and Scomazzoni merely note that right coronary supply is common and left supply rare.

Coronary anastomosis

Anastomoses between branches of coronary arteries, subepicardial or myocardial, and between these arteries and extracardiac vessels are of prime medical import. Clinical experience suggests that anastomoses cannot rapidly provide collateral routes sufficient to circumvent sudden coronary obstruction. It is hence traditional to regard coronary circulation as end-arterial. Nevertheless, anastomosis has long been established particularly between the finer subepicardial rami. According to Gross (1921) such anastomoses may improve during individual life. Those who have investigated coronary arteries by radio-opaque perfusants (Vastesaeger et al 1957 in postmortem hearts; Laurie & Woods 1958 by in vivo coronary radiography), by perfusion with calibrated spherules (Prinzmetal et al 1947) or by subsequent corrosion casts of plastic resins (Baroldi et al 1956, James 1961) have almost all described anastomoses, and in vessels up to 100–200 μm in calibre. Baroldi and Scomazzoni (1967) have tabulated all results reported since 1880; no study denying anastomoses has been recorded since 1957. Some describe anastomoses only between branches of individual coronary arteries but the majority record intercoronary anastomoses. James (1978) considers the evidence conclusive for anastomoses at all levels: subepicardial, myocardial, and subendocardial; the most frequent sites of extramural anastomoses are the apex, the anterior aspect of the right ventricle, posterior aspect of the left ventricle, crux, interatrial and interventricular sulci and between the sinuatrial nodal and other atrial vessels. The functional value of such anastomoses must vary but they appear to become more effective in slowly progressive pathological conditions. Their structure is uncertain; most observations depend on corrosion casts, which suggest that anastomotic vessels are relatively straight in normal hearts, but much coiled in hearts subject to coronary occlusion. Little has been recorded of their microscopic structure; they appear little more than endothelial tubes, without muscles or elastic tissue

Extracardiac anastomoses may connect various coronary branches with other thoracic vessels via the pericardial arteries and arterial vasa vasorum of vessels linking the heart with systemic and pulmonary circulations. The classic study of Hudson et al (1932) showed that coronary injections of India ink could reach the diaphragm through

the aortic vasa vasorum. Similar connections along pulmonary trunks reach the mediastinal and bronchial arteries and also exist along pulmonary veins and venae cavae. These results have been confirmed (Baroldi & Scomazzoni 1967) but the effectiveness of such connections as collateral routes in coronary occlusion is unpredictable.

Coronary arteriovenous anastomoses were reported by Nussbaum (1912). His evidence was indirect but Hirsch (1960) described glomeral structures with typical sphincteric appearances (p. 1468) in cardiac sulci; these must be regarded as at present unproven. Various other forms of 'arteriovenous' connections have been described; Wearn et al (1933) recorded numerous connections through the very thin-walled 'arterial' vessels between the coronary circulation and cardiac cavities, naming them 'myocardial sinusoids' and 'arterioluminal' vessels. They have been confirmed (Watanabe 1960) and indirect evidence of them, from perfusion experiments, dates back to Vieussens (1705). Their value in coronary disease is uncertain.

Histology of coronary arteries

The coronary arteries are highly muscular vessels, but rather variable in their structure, partly on account of their frequent branching and tortuous course. They differ in two respects from other vessels of similar size. The inner elastic lamina, discontinuous and poorly developed at birth, disappears during growth, and bundles of longitudinally oriented muscle are present in the outer part of the intima or the inner part of the media (a boundary between media and intima cannot be identified).

ARCH OF THE AORTA

The aortic arch (10.65, 70) continues the ascending aorta. Its origin, slightly to the right, is level with the upper border of the second right sternocostal joint. The arch first ascends diagonally back and to the left over the anterior surface of the trachea, then back across its left side and finally descends left of the fourth thoracic vertebral body, continuing as the descending thoracic aorta. Its end is level with the sternal end of the second, left costal cartilage (10.28). Thus, the aortic arch lies wholly in the superior mediastinum. It curves around the peduncle of the left lung, and extends upwards to the mid-level of the manubrium of the sternum. Its diameter at the origin is the same as in the ascending aorta, about 28 mm, but it is reduced to 20 mm at the end, after the issue of its large collateral branches. At the border with the thoracic aorta, a small stricture (aortic isthmus), followed by a dilatation, can be recognized. In fetal life the isthmus lies between the origin of the left subclavian artery and the opening of the ductus arteriosus.

Relations

Anteriorly and to the left is the left mediastinal pleura, deep to which it is crossed by four nerves: the left phrenic, left lower cervical vagal cardiac branch, left superior cervical sympathetic cardiac branch and left vagus, in anteroposterior order. As the left vagus crosses the arch its recurrent laryngeal branch hooks below the vessel left and behind (developmentally caudal to) the ligamentum arteriosum and then ascends on the arch's right. The left superior intercostal vein ascends obliquely forwards on the arch, superficial to the left vagus, deep to the left phrenic nerve (10.69). The left lung and pleura separate all these from the thoracic wall. Posterior to the right are the trachea and deep cardiac plexus, the left recurrent laryngeal nerve, oesophagus, thoracic duct and vertebral column. Above, the brachiocephalic, left common carotid and left subclavian arteries arise from its convexity, crossed anteriorly near their origins by the left brachiocephalic vein. Below are the pulmonary bifurcation, left principal bronchus, ligamentum arteriosum (p. 1467), superficial cardiac plexus and left recurrent laryngeal nerve. (Best viewed from the left, the concavity of the aortic arch is the upper curved limit through which structures gain access or exit through the hilum of the left lung.)

The fetal aortic lumen narrows between the origin of the left subclavian artery and the attachment of the ductus arteriosus, as the aortic isthmus; beyond the ductus arteriosus the vessel presents a fusiform aortic spindle, the junction of the two parts being marked inferiorly by an indentation; these features persist variably in adults.

Left lung   *Manubrium sterni*   *Right lung*

Ascending aorta near termination

Left phrenic nerve

Left principal bronchus

Left vagus nerve

Descending thoracic aorta

Superior vena cava

Right phrenic nerve

Lymph nodes

Right principal bronchus

Right vagus nerve

Vena azygos

Oesophagus

Thoracic duct

A right posterior intercostal artery

Fourth thoracic vertebra

10.68 Transverse section through the mediastinum at the level of the lower part of the body of the fourth thoracic vertebra, viewed from above. The deep cardiac plexus of nerves is omitted.

Common carotid arteries   *Internal jugular vein*

Internal jugular vein

Vagus nerve

Inferior thyroid vein

Phrenic nerve

Internal thoracic artery

Superior vena cava

Fibrous pericardium

Serous pericardium

Ascending aorta

Right atrium

Horizontal fissure

Diaphragm

Central tendon

Jugular lymph trunk

Left lymphovenous portal

Subclavian vein

Subclavian artery

Left superior intercostal vein

Vagus nerve

Phrenic nerve

Pulmonary trunk

Right ventricle

Left ventricle

10.69 Dissection to display the heart, great vessels and lungs in situ. The sternum and the sternal ends of the costal cartilages, together with the parietal pleura on each side, have been excised and the mediastinal pleura and parietal layer of the pericardium over the sternocostal surface of the heart have been removed. The lungs have been displaced to expose the heart and the epicardium dissected off the heart and the great vessels.

Second costal cartilage

Lymph node

Superior vena cava

Right phrenic nerve

Tracheal bifurcation

Right vagus nerve

Vena azygos

Oesophagus

Disc between 3rd and 4 thoracic vertebra

Body of 4th thoracic vertebra

Arch of aorta

Left phrenic nerve
Deep cardiac plexus
Superior cervical cardiac branch left sympathetic
Inferior cervical cardiac branch left vagus
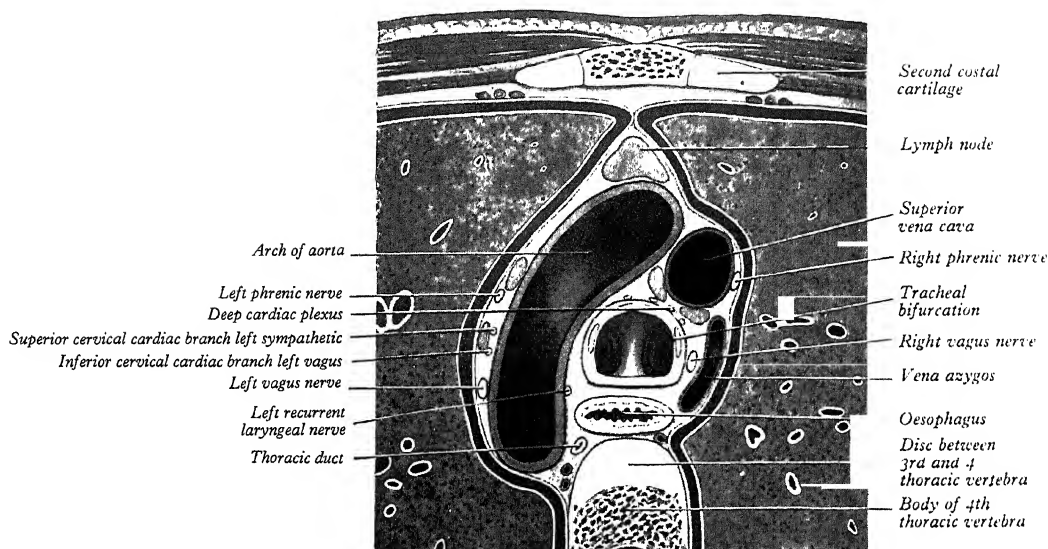Left vagus nerve

Left recurrent laryngeal nerve

Thoracic duct

10.70 Transverse section through the mediastinum at the level of the upper part of the body of the fourth thoracic vertebra, viewed from above.

Variations

The summit of the arch is usually about 2.5 cm below the superior sternal border but may diverge from this. In the infant it is closer to the upper border of the sternum; the same is often the case in old age, because of the dilatation of the vessel. Sometimes the aorta curves over the right pulmonary hilum descending right of the vertebral column, a condition normal in birds; there is usually transposition of thoracic and abdominal viscera. Less often, after arching over the right hilum, it passes behind the oesophagus to its usual position; this is not accompanied by visceral transposition.

Superior thyroid artery

Thyrohyoid
Sternomastoid

Cricothyroid artery
Sternothyroid
Cricothyroid

Superior thyroid artery
Superior thyroid vein
Phrenic nerve
Internal jugular vein
Middle thyroid vein

Thyroid gland, left lobe
Jugular lymph trunk

Subclavian lymph trunks

Common carotid artery

Thoracic duct

Inferior thyroid vein

Arch of aorta
Internal thoracic vein
Internal thoracic artery

Conus elasticus

Isthmus of thyroid gland

Scalenus anterior
Omohyoid inferior belly

Upper trunk of brachial plexus
Vagus nerve

Inferior thyroid veins

Cardiac branch of vagus nerve

Brachiocephalic artery

10.71 Dissection of the lower part of the front of the neck and of the superior mediastinum. The manubrium sterni and the sternal ends of the clavicles and the first costal cartilages have been removed and the pleural sac and lung have been retracted on each side. In this specimen each superior thyroid artery arose from the common carotid artery.

The aorta may divide, as in some quadrupeds, into ascending and descending trunks, the former dividing into three branches to supply the head and upper limbs. Sometimes it divides near its origin, the two branches soon reuniting; the oesophagus and trachea usually pass through the interval between them; this is the normal condition in reptilia and is due to the persistence of a part of the right dorsal aorta which usually disappears (p. 312).

Radiological appearances

The shadow of the arch is easily identified in anteroposterior radiographs (10.48, 49) and its left profile is sometimes called the 'aortic knuckle'. The arch may also be visible in left anterior oblique views enclosing a pale space, 'the aortic window', in which shadows of the pulmonary trunk and its left branch may be visible.

Branches (10.69, 71)

Three branches spring from the vessel's convex aspect: the brachiocephalic trunk, left common carotid and left subclavian arteries (10.69, 71). They may branch from the beginning of the arch or the upper part of the ascending aorta; the distance between these origins varies, the most frequent being approximation of the left common carotid artery to the brachiocephalic trunk (Wright 1969). Primary branches may be reduced to one, more commonly two, the left common carotid arising from the brachiocephalic trunk (7%), or (more rarely) the left common carotid and subclavian arteries arising from a left brachiocephalic or right common carotid and subclavian arising separately, in which case the latter more often branches from the left end of the arch and passes behind the oesophagus (p. 314). The left vertebral artery may arise between the left common carotid and the subclavian. Very rarely, external and internal carotid arteries arise separately, the common carotid being absent on one or both sides; or both carotids and one or both vertebrals may be separate branches. When a 'right aorta' occurs, the arrangement of its three branches is reversed. The common carotids may have a single trunk, the subclavians separate, the right arising from the left end of the arch. Other arteries may branch from it, most commonly one or both bronchial arteries and the arteria thyroidea ima.

An analysis of variation in branches from 1000 aortic arches (Anson 1963) showed in 65% the usual pattern; in 27% a left common carotid shared the brachiocephalic trunk (contrast percentage quoted above); in 2.5% the four large arteries branched separately. The remaining 5% showed a great variety of patterns, the commonest (1.2%) being symmetrical right and left brachiocephalic trunks.

The brachiocephalic (innominate) artery, the largest branch of the aortic arch, is from 4–5 cm in length (10.66, 71, 72), arising from the arch's convexity posterior to the centre of the manubrium sterni; it ascends posterolaterally to the right, at first anterior to the trachea, then on its right. Level with the right sternoclavicular

joint's upper border it forks into the right common carotid and subclavian arteries.

Relations

Anterior are sternohyoid and sternothyroid, the remains of the thymus, left brachiocephalic and right inferior thyroid veins, crossing its root, and sometimes the right vagal cardiac branches, all separating it from the manubrium. Posterior are the trachea below, right pleura above, where the right vagus is posterolateral before passing lateral to the trachea; right lateral are the right brachiocephalic vein, the upper part of the superior vena cava and pleura; left lateral are the thymic remains, the origin of the left common carotid artery, the inferior thyroid veins and the trachea at a higher level.

Branches

The brachiocephalic artery usually has only terminal branches but occasionally an arteria thyroidea ima arises from it, sometimes a thymic or bronchial branch.

Arteria thyroidea ima, small and inconstant, ascends on the trachea to the thyroid isthmus, in which it ends. It may arise from the aorta, right common carotid, subclavian or internal thoracic arteries.
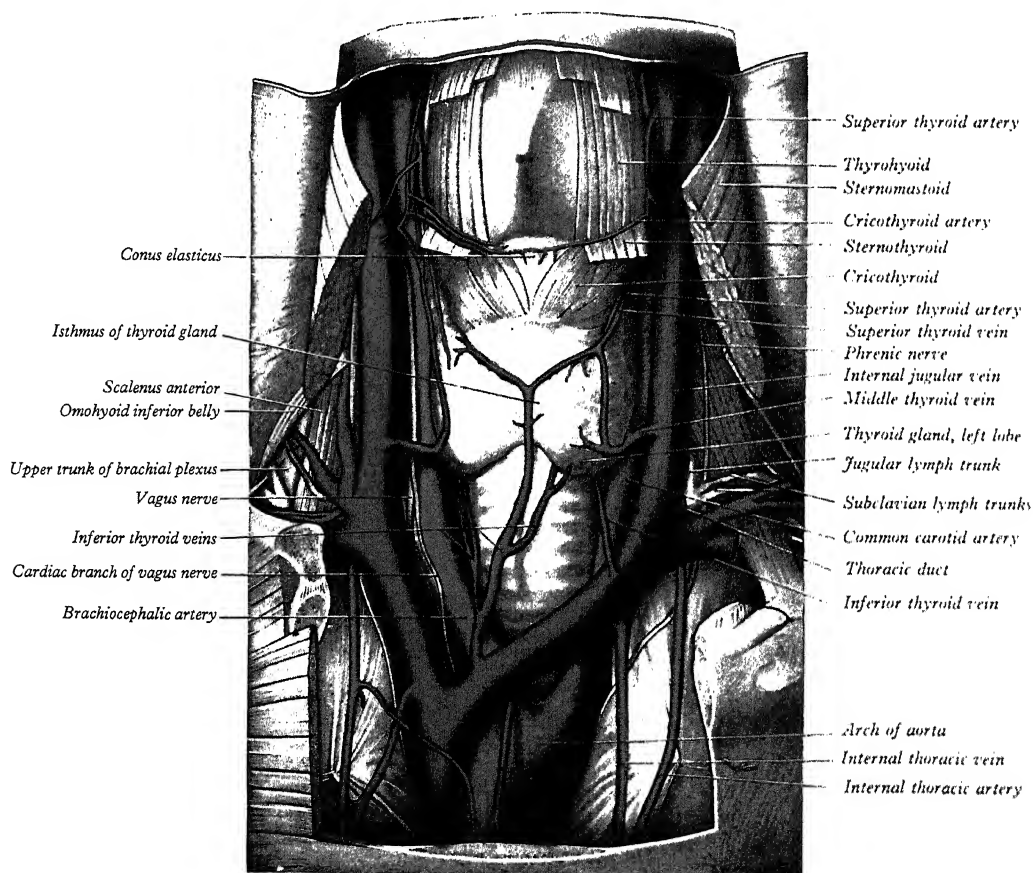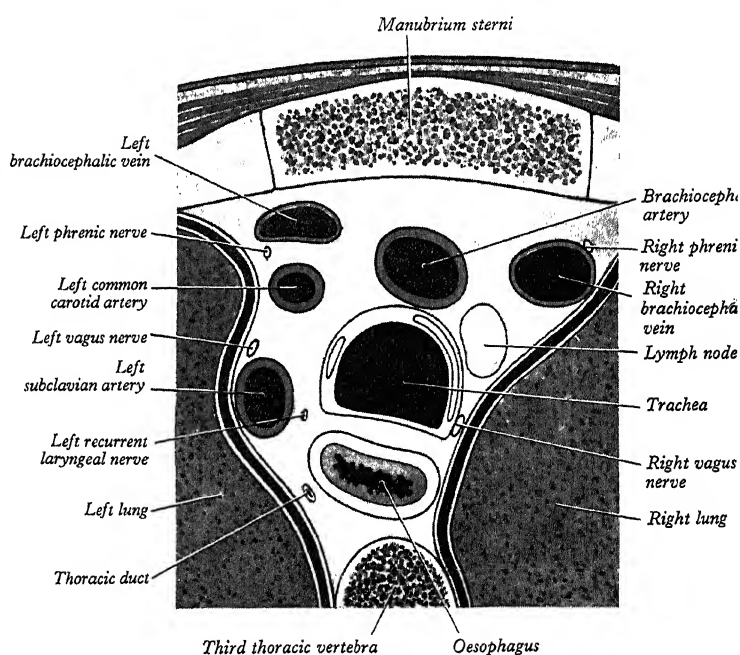

10.72 Transverse section through the superior mediastinum at the level of the body of the third thoracic vertebra, viewed from above.

CAROTID SYSTEM OF ARTERIES

The common carotid artery is a large bilateral vessel supplying head and neck; it ascends to just above the level of the thyroid cartilage's upper border, where it divides into an external carotid, supplying the exterior of the head, face and most of the neck, and an internal carotid, supplying the cranial and orbital contents.

The common and internal carotid arteries, with veins and nerves accompanying them, lie in a cleft bounded posteriorly by cervical transverse processes and attached muscles, medially by the trachea, oesophagus, thyroid gland, larynx and pharyngeal constrictors, anterolaterally by the sternocleidomastoid with, at different levels, omohyoid, sternohyoid, sternothyroid, digastric and stylohyoid muscles.

COMMON CAROTID ARTERIES

The right and left carotid arteries differ in length and origin. The right carotid, exclusively cervical, originates from the brachiocephalic trunk behind the right sternoclavicular joint. The left carotid originates directly from the aortic arch immediately posterolateral to the brachiocephalic trunk and therefore has both thoracic and cervical parts.

Thoracic part of the left common carotid artery (10.71, 72). This part ascends until level with the left sternoclavicular joint,

Superficial temporal, parietal branch
Transverse facial artery
Superficial temporal artery
Maxillary artery
Facial nerve
Posterior auricular artery
Accessory nerve
Sternocleidomastoid
Occipital artery
Internal jugular vein
External carotid artery
Third cervical anterior primary ramus
Internal carotid artery
Splenius capitis
Levator scapulae
Carotid sinus
Fourth cervical anterior primary ramus
Scalenus medius
Ascending cervical artery
Phrenic nerve
Inferior thyroid artery
Scalenus anterior
Superficial cervical artery

Superficial temporal, frontal branch
Facial artery
Hypoglossal nerve
Lingual artery
Nerve to thyrohyoid
Internal laryngeal nerve
Superior thyroid artery
External laryngeal nerve
Vagus nerve
Common carotid artery

Subclavian artery, third part   Suprascapular artery   Thyrocervical trunk   Transmedian cricothyroid arterial anastomosis

10.73 Dissection of the right side of the neck, showing the carotid and subclavian arteries and their branches. The parotid and submandibular glands have been removed together with the lower part of the internal jugular vein, most of the sternocleidomastoid and the upper parts of the stylohyoid and posterior belly of the digastric.

where it enters the neck. It is 20–25 mm long and it lies at first in front of the trachea, then it inclines to the left.

Relations. **Anterior** are the sternohyoid and sternothyroid, the anterior parts of the left pleura and lung, the left brachiocephalic vein and the thymic remnants, separating it from the manubrium; posterior are the trachea, left subclavian artery, left border of the oesophagus, left recurrent laryngeal nerve and thoracic duct. To the **right** are (below) the brachiocephalic trunk and (above) the trachea, inferior thyroid veins and thymic remains; to the **left** are the left vagus and phrenic nerves, left pleura and lung.

Cervical part of both common carotid arteries. Following a similar course (**10.71–74**), it ascends, diverging laterally from behind the sternoclavicular joint to the thyroid cartilage's upper border, where it divides into external and internal carotid arteries (**10.73, 75**). At its division the vessel has a dilatation, the *carotid sinus*, usually involving or restricted to the beginning of the internal carotid; the tunica-media is thinner here and the tunica adventitia, relatively thick, contains many receptor endings of the glossopharyngeal nerve (p. 1250). The sinus is responsive to changes in arterial blood pressure, leading to reflex haemodynamic modification. Its position on the main artery of the brain accounts for its role as a baroreceptor in control of intracranial pressure. The *carotid body*, behind the common carotid bifurcation, a small, reddish-brown structure, is a 'chemoreceptor'. (See Adams 1958 for a comparative account and p. 971 for modern views on its ultrastructure and function.)

In the lower neck the common carotids are separated by a narrow gap into which projects the trachea; above this the thyroid gland, larynx and pharynx project between them. Each is contained in a carotid sheath (p. 804), continuous with the deep cervical fascia and

of loose texture, though that actually around the artery is denser. This sheath encloses also the internal jugular vein and vagus nerve; the vein lies lateral to the artery, the nerve between them and posterior to both.

Relations. The artery is crossed **anterolaterally**, level with the cricoid cartilage, by the intermediate tendon (sometimes the superior belly) of the omohyoid. Below this muscle it is sited deeply, covered by skin, superficial fascia, platysma, deep cervical fascia, the sternocleidomastoid, sternohyoid and sternothyroid. Above the omohyoid it is more superficial, covered merely by skin, superficial fascia, platysma, deep cervical fascia and the medial margin of sternocleidomastoid and is crossed obliquely from its medial to lateral side by the sternocleidomastoid branch of the superior thyroid artery. In front of, or embedded in, the carotid sheath is the superior root of the ansa cervicalis, joined by its inferior root from the second and third cervical spinal nerves and crossing the vessel obliquely. The superior thyroid vein usually crosses near the artery's end, the middle thyroid vein a little below cricoid level; the anterior jugular vein crosses it above the clavicle, separated by sternohyoid and sternothyroid. **Posterior** are the fourth to sixth cervical transverse processes, and attached to them the longus colli and longus capitis and tendinous slips of scalenus anterior; the sympathetic trunk and ascending cervical artery are between the common carotid artery and the muscles. Below the level of the sixth cervical vertebra the artery is in an angle between the scalenus anterior and longus colli, anterior to the vertebral vessels, inferior thyroid and subclavian arteries, sympathetic trunk and, on the left, thoracic duct. **Medial** are the oesophagus, trachea, inferior thyroid artery and recurrent laryngeal nerve and, at a higher level, the larynx and pharynx; the

1514

thyroid gland overlaps it anteromedially. **Lateral** is the internal jugular vein, which in the lower neck is also anterior to the artery; posterolaterally in the angle between artery and vein is the vagus nerve.

On the right, low in the neck, the recurrent laryngeal nerve crosses obliquely behind the artery; the right internal jugular vein diverges from it below but the left vein approaches and often overlaps its artery.

Variations

In about 12% the right common carotid artery arises above the level of the sternoclavicular joint or it may be a separate branch from the aorta; again it may arise with its fellow. The left common carotid artery varies in origin more than the right; it may arise with the brachiocephalic (see also p. 1513). Division of the common carotid may occur higher, near the level of the hyoid bone, more rarely at a lower level alongside the larynx. Very rarely it ascends without division, either the external or internal carotid being absent. Rarely, also, it is replaced by separate external and internal carotid arteries arising directly from the aorta, on one side or bilaterally.

The common carotid artery usually has no branches but the vertebral, superior thyroid (**10.71**) or its laryngeal branch, ascending pharyngeal, inferior thyroid or occipital may be branches of it.

EXTERNAL CAROTID ARTERY

This artery (**10.73–75**) begins lateral to the thyroid cartilage's upper border, level with the disc between the third and fourth cervical vertebrae. A little curved, and with a gentle spiral, it first ascends slightly forwards and then inclines backwards and a little laterally, to pass midway between the mastoid tip and the mandibular angle where, in the substance of the parotid gland behind the mandible's neck, it divides into the superficial temporal and maxillary arteries. It diminishes rapidly in calibre due to its many large branches. In children it is smaller than the internal carotid but in adults the two are of almost equal size. At its origin, it is in the carotid triangle (p. 1521) and lies anteromedial to the internal carotid but becomes anterior, then lateral to this as it ascends. At mandibular levels the styloid process and its attached structures intervene between the vessels, the internal carotid being deep and the external carotid superficial to the styloid. A finger tip placed at the carotid triangle perceives a powerful arterial pulsation: beneath the finger lie the termination of the common carotid, the origins of external and internal carotids and the stems of the external carotid's initial branches.

Relations. Superficial to the artery in the carotid triangle are: the skin, superficial fascia, the loop between the facial nerve's cervical branch and the transverse cutaneous nerve of the neck, deep fascia and the anterior margin of sternocleidomastoid; it is crossed by the hypoglossal nerve and its vena comitans and by the lingual (common), facial and sometimes the superior thyroid veins. Leaving the triangle it is crossed by the posterior belly of the digastric and stylohyoid and ascends between this muscle and the posteromedial surface of the parotid gland, which it enters, lying medial to the facial nerve and the junction of the superficial temporal and maxillary veins. **Medial** to the artery are at first the pharyngeal wall, superior laryngeal nerve and ascending pharyngeal artery; at a higher level the internal carotid artery is separated from the external by the styloid process, styloglossus and stylopharyngeus, glossopharyngeal nerve, pharyngeal branch of vagus nerve and part of the parotid gland (**10.74**). The relation of the artery to the parotid gland is controversial, many clinicians asserting that it is often medial to it rather than in it. It seems that both relations occur at about equal frequency (Gulfarth & Graumann 1975).

Branches (**10.73, 74, 77**). These are:

Superior thyroid	Occipital
Ascending pharyngeal	Posterior auricular
Lingual	Superficial temporal
Facial	Maxillary.

SUPERIOR THYROID ARTERY (10.73)

This arises from the front of the external carotid artery just below
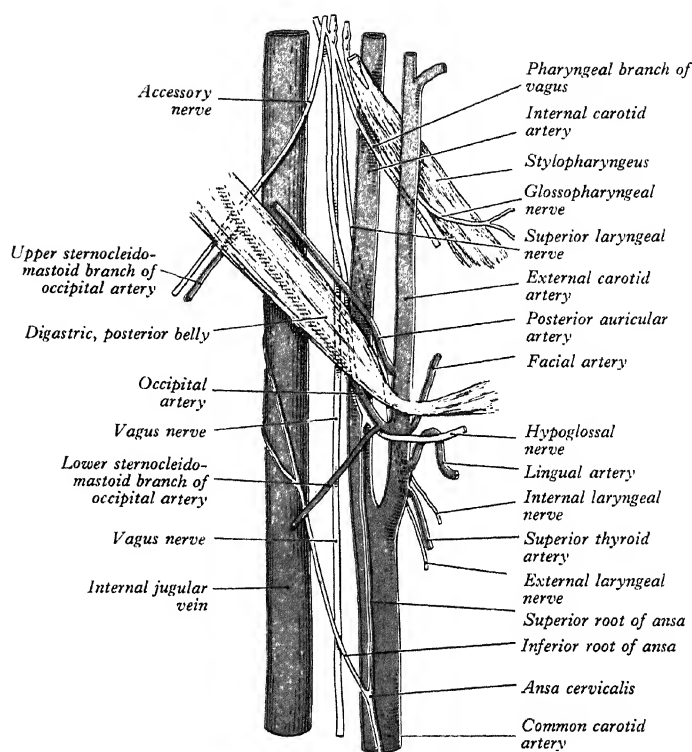
10.74 The structures crossing the internal jugular vein and carotid arteries and those intervening between the external and internal carotid arteries.
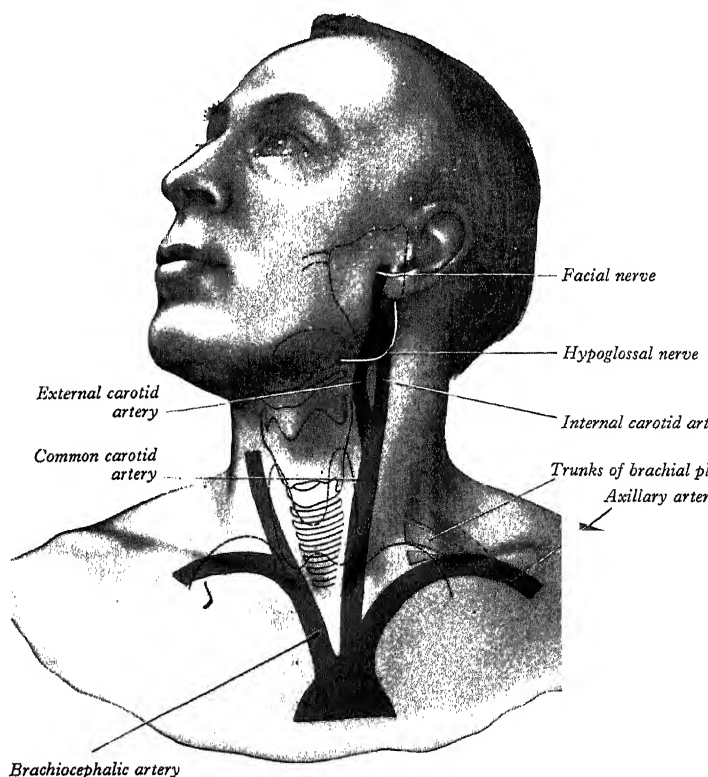
10.75 The surface projection of some of the larger structures in the face and neck. Note that the parotid gland and duct, and submandibular and thyroid glands and the apices of the lungs are shown as interrupted outlines; the hyoid bone and the thyroid, cricoid and tracheal cartilages are indicated by continuous outlines.

the level of the greater cornu of the hyoid, dividing into terminal branches at the apex of the thyroid lobe, but it may issue from the common carotid (10.71).

Relations. From an origin under the sternocleidomastoid it descends forwards in the carotid triangle along the lateral border of the thyrohyoid, covered by skin, platysma and fasciae and then deep to the omohyoid, sternohyoid and sternothyroid. Medial are the constrictor pharyngis inferior and external laryngeal nerve; the nerve is often posteromedial.

Branches. The artery supplies the adjacent muscles and the thyroid gland; it anastomoses with its fellow and the inferior thyroid arteries. Glandular branches are anterior, along the medial side of the upper pole of the lateral lobe, supplying mainly the anterior surface, a branch crossing above the isthmus to anastomose with its fellow; and posterior descending on the posterior border, supplying the medial and lateral surfaces and anastomosing with the inferior thyroid artery. Sometimes a lateral branch supplies the lateral surface. The artery also has named branches: infrahyoid, superior laryngeal, sternocleidomastoid and cricothyroid.

Infrahyoid artery. This is small, runs along the lower border of the hyoid deep to thyrohyoid and anastomoses with its fellow. It can be replaced by two or more branches.

Sternocleidomastoid artery. Frequently arising from the external carotid, it descends laterally across the carotid sheath.

Superior laryngeal artery. Accompanying the internal laryngeal nerve deep to the thyrohyoid, it pierces the lower part of the thyrohyoid membrane, supplies the larynx and anastomoses with its fellow and the inferior laryngeal branch of the inferior thyroid.

Cricothyroid artery. A small artery, it crosses high on the cricothyroid ligament, communicating with its fellow.

ASCENDING PHARYNGEAL ARTERY

This, the smallest branch of the external carotid, is a long, slender vessel, arising posteriorly near the external carotid's origin and ascending between the internal carotid artery and pharynx to the cranial base (10.84); it is crossed by the styloglossus and stylopharyngeus, with longus capitis posterior to it; it anastomoses with the facial artery's ascending palatine branch. Its named branches are: pharyngeal, inferior tympanic and meningeal. Numerous small branches supply the longus capiti and longus colli, the sympathetic trunk, hypoglossal, glossopharyngeal and vagus nerves and cervical lymph nodes, anastomosing with branches of the ascending cervical and vertebral arteries.

Pharyngeal arteries. Three or four supply the constrictors and stylopharyngeus. A variable ramus supplies the palate and may replace the facial's ascending palatine branch; it descends forwards between the superior border of the superior constrictor and the

levator veli palatini, accompanying the latter to the soft palate; it gives minute branches to the tonsil and one to the auditory tube.

Inferior tympanic artery. A small branch, it traverses the temporal canaliculus for the tympanic branch of the glossopharyngeal nerve to supply the tympanic cavity's medial wall.

Meningeal branches. These small vessels to the nerves, dura mater and adjacent bone enter the cranium through the foramen lacerum, jugular foramen and hypoglossal canal. They supply the nerves in these passages and their surrounding tissues. One of them, the *posterior meningeal artery*, which reaches the cerebellar fossa via the jugular foramen, is usually regarded as the terminal branch of the ascending pharyngeal artery.
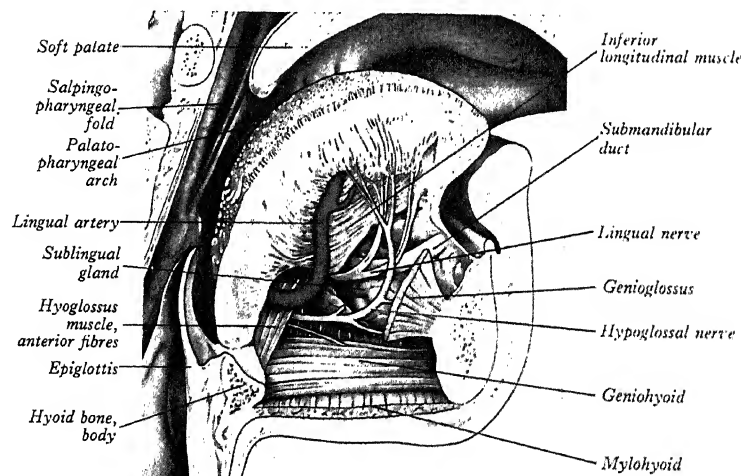
LINGUAL ARTERY

This vessel, bringing the chief supply to the tongue and buccal floor of the mouth, arises anteromedially from the external carotid opposite the tip of the hyoid's greater cornu, between the superior thyroid and facial arteries (10.73, 74). Ascending medially at first, it loops down and forwards, passes medial to the posterior border of the hyoglossus and horizontally forwards deep to it and, ascending again almost vertically, courses sinuously forwards on the tongue's inferior surface as far as its tip (10.76). Its relation to the hyoglossus naturally divides the vessel into descriptive 'thirds'.

Relations. In its *first part* the lingual artery is in the carotid triangle; superficial to it are the skin, fascia and platysma; the middle pharyngeal constrictor is medial. It ascends a little medially, then descends to the level of the hyoid bone, its loop crossed externally by the hypoglossal nerve. Its *second part* passes along the hyoid's upper border, deep to the hyoglossus, the tendons of digastric and stylohyoid, the lower part of the submandibular gland and posterior part of the mylohyoid; the hyoglossus separates it from the hypoglossal nerve and its vena comitans; here its medial aspect adjoins the middle constrictor and crosses the stylohyoid ligament; it is accompanied by lingual veins (p. 1580). The *third part* is the *arteria profunda linguae*, which turns upward near the anterior border of the hyoglossus, passing forwards close to the inferior lingual surface near the frenulum, accompanied by the lingual nerve. Medial to it is the genioglossus, lateral to it the longitudinalis linguae inferior, below it the lingual mucous membrane. Near the lingual tip it anastomoses with its fellow. Its named branches are suprahyoid, dorsal lingual and sublingual.

The lingual artery often arises with the facial or, less often, with the superior thyroid artery. It may be replaced by a ramus of the maxillary artery.

Suprahyoid artery. This is very small and runs along the hyoid's upper border to anastomose with the contralateral artery.

Soft palate · Salpingo-pharyngeal fold · Palato-pharyngeal arch · Lingual artery · Sublingual gland · Hyoglossus muscle, anterior fibres · Epiglottis · Hyoid bone, body · Inferior longitudinal muscle · Submandibular duct · Lingual nerve · Genioglossus · Hypoglossal nerve · Geniohyoid · Mylohyoid

10.76 Dissection of the left half of the tongue from the medial side, exposing the end of the second part and the beginning of the third part of the left lingual artery and adjoining structures, in an edentulous subject.

Dorsal lingual arteries. Usually two or three small vessels, these arise medial to the hyoglossus, and ascend to the posterior part of the lingual dorsum to supply its mucous membrane, palatoglossal arch, tonsil, soft palate and epiglottis; they anastomose with the opposite vessels.

Sublingual artery. Arising at the anterior margin of hyoglossus, it goes forward between the genioglossus and mylohyoid to the sublingual gland, supplying this, the mylohyoid and the buccal and gingival mucous membranes. One branch pierces the mylohyoid and joins the submental branches of the facial artery; another courses through the mandibular gingiva to anastomose with its fellow. From this anastomosis issues a single artery which enters the lingual foramen of the mandible, situated in the midline on the posterior aspect of the symphysis, immediately above the genial tuberculus (McDonnell et al 1994).

FACIAL ARTERY

This artery (also known as *external maxillary*) arises anteriorly from the external carotid in the carotid triangle above the lingual artery and immediately above the greater cornu of the hyoid bone (10.77, 84). Medial to the mandibular ramus it arches upwards and grooves the posterior aspect of the submandibular gland; it then turns down again between the gland and the medial pterygoid. Reaching the surface of the mandible it curves round its inferior border, anterior to the masseter, to enter the face. Here it ascends forwards across the mandible and buccinator to traverse a cleft in the modiolus (p. 796) near the buccal angle. It then ascends the side of the nose and ends at the medial palpebral commissure, supplying the lacrimal sac and joining the dorsal nasal branch of the ophthalmic artery. The artery is very sinuous throughout: in the neck perhaps to adapt to the movements of the pharynx during deglutition and on the face to movements of the mandible, lips and cheeks. Distal to its superior branch it is termed the *angular artery*. Facial artery pulsation is most palpable where it crosses the mandibular base and, between thumb and finger, near the buccal angle.

Relations. In the neck, at its origin, the artery is superficial, covered by the skin, platysma and fasciae and often crossed by the hypoglossal nerve. It runs up and forwards, deep to the digastric and the stylohyoid and posterior part of the submandibular gland. At first on the middle pharyngeal constrictor, it may reach the lateral surface of the styloglossus, separated there from the tonsil only by this muscle and the lingual fibres of the superior constrictor. Thence it descends to the lower border of the mandible in a lateral groove on the submandibular gland. In the face, where, as noted, its pulse can be felt as it crosses the mandible, it is superficial and at first just beneath the platysma. It is covered by skin, the fat of the cheek and near the buccal angle by superficial modiolar muscles (p. 796). Deep to it are the buccinator and levator anguli oris; it may pass over or through the levator labii superioris. Terminally it is embedded in the levator labii superioris alaeque nasi. The facial vein is posterior, in a more direct course across the face; at the anterior border of the masseter the two are in contact; in the neck the vein is superficial. Branches of the facial nerve cross forwards over the artery, which supplies the muscles and tissues of the face, submandibular gland, tonsil and soft palate. Its branches are cervical and facial.

Cervical branches

Ascending palatine artery (10.84). Starting near the facial's origin, it ascends between the styloglossus and stylopharyngeus to the side of the pharynx, along which it ascends between the superior constrictor and the medial pterygoid towards the cranial base. Near the levator veli palatini it bifurcates: one branch follows this muscle, winds over the upper border of the superior constrictor, supplies the soft palate and anastomoses with its fellow and the greater palatine branch of the maxillary artery; the other branch pierces the superior constrictor to supply the tonsil and pharyngotympanic tube, joining with tonsillar and ascending pharyngeal arteries.

Tonsillar artery. The main supply to the tonsil, it sometimes arises from the ascending palatine, though is usually separate; it ascends between the medial pterygoid and styloglossus and at the latter's upper border it perforates the superior constrictor and ramifies in the tonsil and posterior lingual musculature.

Glandular branches. Three or four large vessels, they supply the submandibular salivary gland and lymph nodes, adjacent muscles and skin.

Submental artery. The largest cervical branch, it arises as the facial separates from the submandibular gland, turning forwards on the mylohyoid (10.77) below the mandible. It supplies the surrounding muscles and anastomoses with a sublingual branch of the lingual and mylohyoid branch of the inferior alveolar arteries; at the chin it ascends the mandible, dividing into superficial and deep branches which anastomose with the inferior labial and mental arteries, supplying the chin and lower lip.

Facial branches

Inferior labial artery (10.77). Arising near the buccal angle, it passes up and forwards under the depressor anguli oris, penetrates the orbicularis oris and runs sinuously near the lower lip's margin between the muscle and the mucous membrane. It supplies the inferior labial glands, mucous membrane and muscles, anastomosing with its fellow and the mental branch of the inferior alveolar artery.

Superior labial artery (10.77). Larger and more tortuous than the inferior, it has a similar course along the superior labial margin between the mucous membrane and the orbicularis oris; it anastomoses with its fellow, supplying the upper lip, a septal branch, which ramifies antero-inferiorly in the nasal septum, and an alar branch.

Lateral nasal artery (10.77). Branching from the facial as it ascends the side of the nose, it supplies the nasal ala and dorsum, anastomosing with its fellow, the septal and alar branches of the superior labial, dorsal nasal ramus of the ophthalmic and infraorbital branch of the maxillary artery. It may be replaced by several small branches or arise from the superior labial, diverging from its septal branch (as in 10.77).

Facial anastomoses. These are numerous not only with corresponding contralateral branches but also: in the neck, with the sublingual branch of the lingual, ascending pharyngeal and palatine branch of the maxillary; on the face, with the mental branch of the inferior alveolar, transverse facial branch of the superficial temporal, infraorbital branch of the maxillary and dorsal nasal branch of the ophthalmic. The anastomoses in the lips are by main trunks, an important fact in labial injuries.
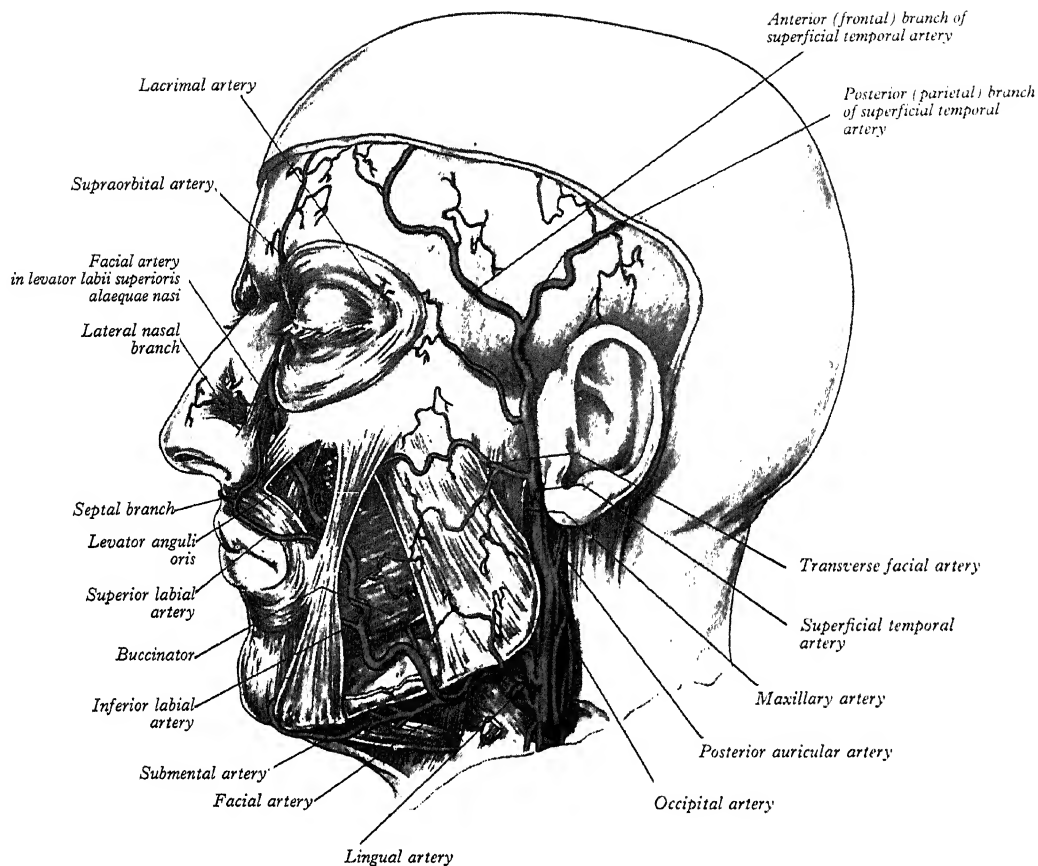
Variations. The facial artery may arise with the lingual, as a linguo-facial trunk. It varies in size and supply to the face: it may end as the submental artery and often extends only to the buccal angle. The deficiency is then filled by branches of neighbouring arteries. In 110 human fetuses a common linguo-facial trunk occurred in 43%; in 42% the facial did not reach the medial orbital angle, ending as a superior (20%) or inferior (22%) labial artery (Kozielec & Józwa 1977).

OCCIPITAL ARTERY

This artery arises posteriorly from the external carotid, about 2 cm from its origin; at first medial to the posterior belly of the digastric, it ends posteriorly in the scalp (10.78).

Course and relations. At its origin, the artery is crossed superficially by the hypoglossal nerve, winding round it from behind. It goes back, up and deep to the posterior digastric belly, crossing the internal carotid, internal jugular vein, hypoglossal, vagal and accessory nerves (10.78). Between the transverse process of the atlas and temporal mastoid process it reaches the lateral border of the rectus capitis lateralis. It then runs in the temporal bone's occipital groove, medial to the mastoid process and attachments of the sternocleidomastoid, splenius capitis, longissimus capitis and digastric, lying successively on the rectus capitis lateralis, obliquus superior and semispinalis capitis. Finally, accompanied by the greater occipital nerve, it turns up to pierce the fascia connecting the cranial attachments of the trapezius and sternocleidomastoid, ascends tortuously in the dense superficial fascia of the scalp and divides into many branches. Its branches are as follows.

Sternocleidomastoid branches. Two branches are usual, the lower arising near the origin of the occipital but sometimes directly from the external carotid. It descends backwards over the hypoglossal nerve and internal jugular vein, enters the sternocleidomastoid, and anastomoses with the sternocleidomastoid branch of the superior thyroid. The upper branch arises as the occipital crosses the accessory

Anterior (frontal) branch of
superficial temporal artery

Lacrimal artery

Posterior (parietal) branch
of superficial temporal
artery

Supraorbital artery,

Facial artery
in levator labii superioris
alaequae nasi

Lateral nasal
branch

Septal branch

Levator anguli
oris

Superior labial
artery

Buccinator

Inferior labial
artery

Submental artery

Facial artery

Transverse facial artery

Superficial temporal
artery

Maxillary artery

Posterior auricular artery

Occipital artery

Lingual artery

10.77 The arteries of the left side of the face and their main branches. Many of the postmodiolar muscles and part of the modiolus (through which the facial artery passes) have been resected. Note the less usual origin of lateral nasal branch in this specimen.
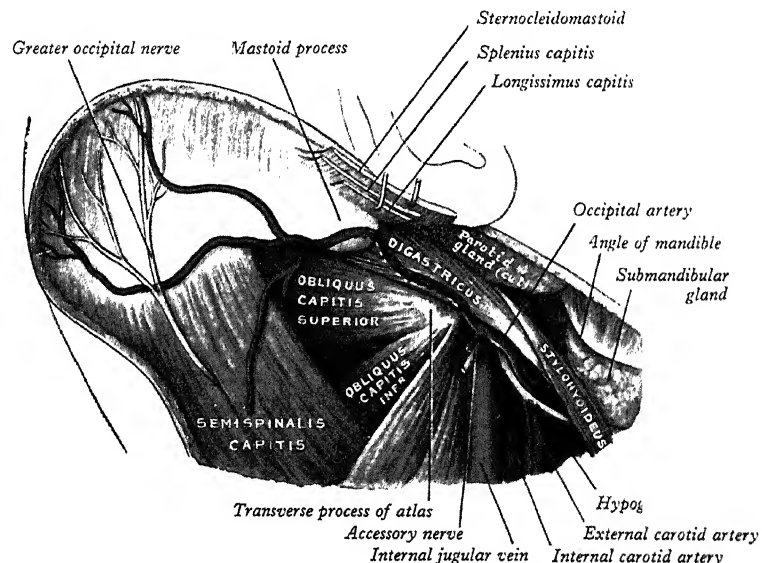
nerve, running down and backwards superficial to the internal jugular vein. It enters the deep surface of the sternocleidomastoid with the accessory nerve.

Mastoid artery. Small in size and sometimes absent, it enters the cranial cavity via the mastoid foramen, supplying the mastoid air cells and dura mater.

Stylomastoid artery. This branches from the occipital in two-thirds of subjects (p. 1520).

Auricular branch. It supplies the medial aspect of the auricle, anastomosing with the posterior auricular artery.

Muscular branches. These supply the digastric, stylohyoid, splenius, longissimus capitis and neighbouring muscles.

Sternocleidomastoid

Greater occipital nerve   Mastoid process

Splenius capitis

Longissimus capitis

Occipital artery

Angle of mandible

Submandibular
gland

DIGASTRICUS

OBLIQUUS
CAPITIS
SUPERIOR

Parotid
gland (cut)

OBLIQUUS
CAPITIS
INFR

STYLOHYOIDEUS

SEMISPINALIS
CAPITIS

Transverse process of atlas
Accessory nerve
Internal jugular vein

Hypog

External carotid artery

Internal carotid artery

10.78 Dissection to show the course of the occipital artery. The upper and lower sternocleidomastoid branches of the artery have been transected and are not labelled.

Descending branch (10.78). This arises where the occipital adjoins the obliquus superior, dividing into superficial and deep branches. The superficial ramus passes deep to the splenius, anastomosing with the superficial branch of the transverse cervical artery; the deep ramus descends between the semispinales capitis et cervicis, anastomosing with both the vertebral and the deep cervical artery (from the costocervical trunk) (10.84).

Meningeal branches. They enter the cranium via the jugular foramen and condylar canal to supply the dura mater and bone of the posterior cranial fossa and the caudal four cranial nerves.

Occipital branches. Tortuous terminal branches distributed to the scalp as far as the vertex, they run between the skin and the occipital belly of the occipitofrontalis, anastomosing with the opposite occipital, posterior auricular and temporal arteries and supplying the occipital belly of the occipitofrontalis, skin and pericranium. There may be a meningeal lateral branch, traversing the parietal foramen.

POSTERIOR AURICULAR ARTERY

This small vessel branches posteriorly from the external carotid just above the digastric and stylohyoid (10.77). It ascends between the parotid gland and the styloid process to the groove between the auricular cartilage and mastoid process, dividing into auricular and occipital branches. As well as supplying the digastric, stylohyoid, sternocleidomastoid, and parotid gland, the posterior auricular artery has three named branches.

Stylomastoid artery. An indirect branch of the posterior auricular in about a third of subjects (Blunt 1954), it enters the stylomastoid foramen to supply the facial nerve, tympanic cavity, mastoid antrum and air cells, and semicircular canals. In the young its posterior tympanic ramus forms a circular anastomosis with the anterior tympanic artery (see below).

Auricular branch. Ascending deep to auricularis posterior, it ramifies on the cranial aspect of the auricle; some branches pierce this, others curve round it to supply its lateral aspect.

Occipital branch. It passes laterally across the mastoid process, turning back over the sternocleidomastoid to supply the occipital belly of the occipitofrontalis and scalp above and behind the ear; it anastomoses with the occipital artery.

SUPERFICIAL TEMPORAL ARTERY

This, the smaller terminal branch of the external carotid, begins in the parotid gland behind the mandible's neck, crosses the posterior root of the zygomatic process of the temporal bone and about 5 cm above this divides into anterior and posterior branches (10.73).

Relations. As it crosses the zygoma it is covered by the auricularis anterior; in the parotid gland temporal and zygomatic branches of the facial nerve cross it; in the scalp it is accompanied by corresponding veins, and just posterior to it lies the auriculotemporal nerve.

Branches. The superficial temporal supplies the parotid gland, temporomandibular joint and masseter and it also has several named branches.

Transverse facial artery (10.77). Arising before the superficial temporal emerges from the parotid gland, it traverses the gland, crosses the masseter between the parotid duct and the zygomatic arch, accompanied by one or two facial nerve branches, and divides into numerous branches supplying the parotid gland and duct, masseter and skin, anastomosing with the facial, masseteric, buccal, lacrimal and infraorbital arteries.

Anterior auricular branches. These are distributed to the lobule and anterior part of the auricle and the external acoustic meatus.

Zygomatico-orbital artery. Sometimes from the middle temporal, it skirts the upper border of the zygomatic arch between two layers of temporal fascia to the lateral orbital angle. It supplies the orbicularis oculi, and anastomoses with the lacrimal and palpebral branches of the ophthalmic artery.

Middle temporal artery. This branches just above the zygomatic arch, perforates the temporal fascia, supplies the temporalis and anastomoses with the deep temporal branches of the maxillary.

Frontal (anterior) branch. Meandering towards the frontal tuberosity, it supplies muscles, skin and pericranium in this region. It

anastomoses with its fellow and the supraorbital and supratrochlear arteries.

Parietal (posterior) branch. Larger than the frontal, it curves up and back, superficial to the temporal fascia, anastomosing with its fellow and the posterior auricular and occipital arteries.

Variation

Variation in the superficial temporal artery is largely in the relative sizes of the frontal, parietal and transverse facial branches; the first two may be absent, the transverse facial may replace a shortened facial artery. Variations in fetal material have been described by Kozielec and Józwa (1976).

Clinical anatomy

Crossing the zygomatic process the artery is palpable through skin and fascia and is easily compressed here to control temporal haemorrhage. This vessel and other arteries supplying the scalp from below are well protected by dense tissue. Rarely are all implicated in a scalping injury and its branches anastomose so freely that a partially detached scalp may be replaced with reasonable hope of success as long as one vessel is intact. In craniotomy, incisions should be convex upwards to include the superficial temporal artery in the flap. In carotid angiograms branches of the superficial temporal and middle meningeal arteries are superimposed, but are distinguishable by the straighter course, lack of anastomoses and narrower calibre in the meningeal branches (Dominić-Stošić & Jeličić 1974).

MAXILLARY (INTERNAL MAXILLARY) ARTERY

This, the larger terminal branch of the external carotid, arises behind the mandibular neck, at first embedded in the parotid gland; it then passes medial to the mandibular neck and superficial or deep to the lower head of the lateral pterygoid to reach the pterygopalatine fossa, usually passing between the two heads of the lateral pterygoid (10.79). It has mandibular, pterygoid and pterygopalatine segments, related sequentially to bone, muscle and bone, a useful indication of its branches.

The **first, mandibular, part** is horizontal and passes between the mandible's neck and the sphenomandibular ligament, parallel with and slightly below the auriculotemporal nerve; it crosses the inferior alveolar nerve and skirts the lower border of the lateral pterygoid.

The **second, pterygoid, part** ascends obliquely forwards medial to the temporalis and superficial to the lower head of the lateral pterygoid; it is often deep to the latter, lying between it and branches of the mandibular nerve and it may then project as a lateral loop between the two parts of the lateral pterygoid.

The **third, pterygopalatine, part** passes between the heads of the lateral pterygoid and through the pterygomaxillary fissure into the pterygopalatine fossa, where it is situated anterior to the pterygopalatine ganglion.
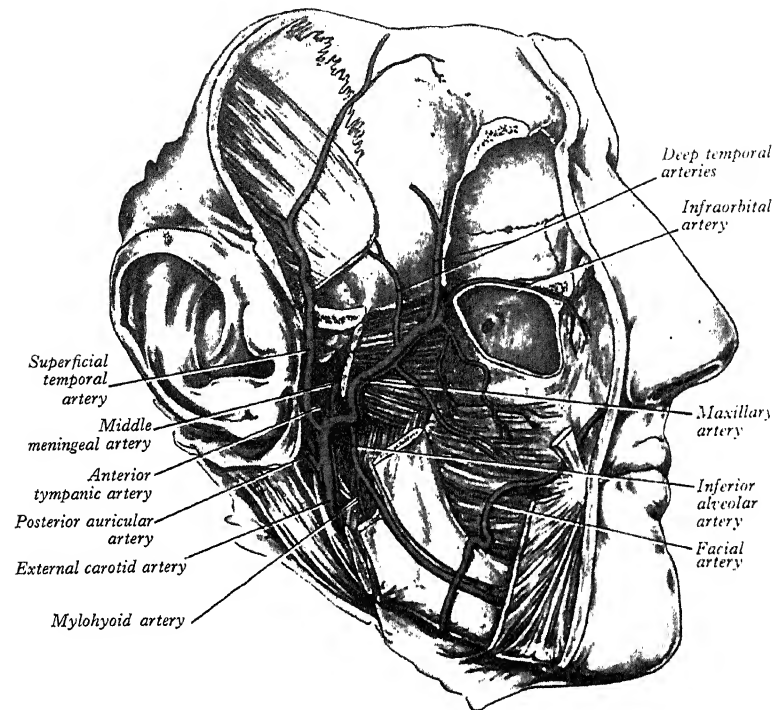
Branches. The artery is distributed to the mandible, maxilla, teeth, muscles of mastication, palate, nose and cranial dura mater. Its branches form three groups, corresponding with its parts.

Branches of the first part (10.79)

Deep auricular artery. Often arising with the anterior tympanic, it ascends in the parotid gland behind the temporomandibular joint, pierces the cartilaginous or osseous wall of the external acoustic meatus and supplies its cuticular lining, the exterior of the tympanic membrane and the joint.

Anterior tympanic artery. Ascending behind the temporomandibular joint, it enters the tympanic cavity through the petrotympanic fissure and ramifies on the interior of the tympanic membrane, forming a vascular circle around it with the posterior tympanic branch of the stylomastoid; it anastomoses with twigs of the artery of the pterygoid canal and caroticotympanic branches of the internal carotid artery in the mucosa of the tympanic cavity.

Middle meningeal artery. Largest of the meningeal arteries, it ascends between the sphenomandibular ligament and lateral pterygoid, passes between the roots of the auriculotemporal nerve and may lie lateral to the tensor veli palatini before entering the cranial cavity through the foramen spinosum. It then runs in an anterolateral groove on the squamous part of the temporal bone, dividing into frontal and parietal branches. The *frontal (anterior) branch,* the

15

Deep temporal
arteries

Infraorbital
artery

Superficial
temporal
artery

Middle
meningeal artery

Anterior
tympanic artery

Posterior auricular
artery

External carotid artery

Mylohyoid artery

Maxillary
artery

Inferior
alveolar
artery

Facial
artery

10.79 The right maxillary artery. An extensive dissection has been carried out, involving the removal of the parotid gland, the zygomatic arch, part of the ramus of the mandible, the lateral walls of the orbit and maxillary sinus and the orbital contents.

larger, crosses the greater wing of the sphenoid, reaches a groove or canal in the parietal's sphenoidal angle and divides into branches between the dura mater and cranium, some ascending to the vertex, others to the occipital region. One ascending branch grooves the parietal bone about 15 mm behind the coronal suture, corresponding approximately to the precentral sulcus. The *parietal* (*posterior*) *branch* curves back on the squamous temporal bone, reaching the lower border of the parietal anterior to its mastoid angle and dividing to supply the posterior parts of the dura mater and cranium. These branches anastomose with their fellows and with the anterior and posterior meningeal arteries.

In the cranial cavity the artery has the following branches:

- Numerous *ganglionic branches* supply the trigeminal ganglion and roots.
- A *petrosal branch* enters the hiatus for the greater petrosal nerve and supplies the facial nerve, ganglion and tympanic cavity, anastomosing with the stylomastoid artery (p. 1519).
- A *superior tympanic artery* runs in the canal for the tensor tympani, supplying both muscle and the mucosa lining the canal.
- *Temporal branches* traverse minute foramina in the sphenoid's greater wing and anastomose with deep temporal arteries.
- An *anastomotic branch* (p. 1526) enters the orbit lateral in the superior orbital fissure, anastomosing with a recurrent branch of the lacrimal artery; enlargement of this anastomosis explains an occasional origin of the lacrimal from the middle meningeal artery.

Apart from these and a supply to the dura mater, the middle meningeal artery is predominantly periosteal, supplying bone and red bone marrow.

Surface anatomy (10.79). The middle meningeal artery enters the skull medial to the zygoma's midpoint, dividing 2 cm above this. From here the frontal branch runs first up and forwards to the pterion and then up and back towards a point midway between the inion and nasion. The parietal branch runs up and back towards the lambda.

Clinical anatomy. The middle meningeal artery may be torn in temporal fractures or by injuries separating the dura mater from the bone, followed by haemorrhage between them. Trephining may be necessary to reduce cerebral compression.

Accessory meningeal artery. This may arise from the maxillary or the middle meningeal. It enters the cranial cavity through the foramen ovale, supplying the trigeminal ganglion, dura mater and bone, but its main distribution is extracranial (Baumel & Beard 1961), principally the medial pterygoid, lateral pterygoid (upper head), tensor veli palatini, sphenoid bone (greater wing and pterygoid processes), mandibular nerve and otic ganglion. It is sometimes replaced by separate small arteries.

Inferior alveolar (dental) artery. Descending posterior to the inferior alveolar nerve, to the mandibular foramen, here it is between bone laterally and the sphenomandibular ligament medially. Before entering the foramen it has a mylohyoid branch, which pierces the sphenomandibular ligament to descend with the mylohyoid nerve in its groove on the mandibular ramus; it ramifies superficially on the muscle and anastomoses with the facial's submental branch. The inferior alveolar artery then traverses the mandibular canal with the inferior alveolar nerve and divides into the incisor and mental branches near the first premolar. The incisor branch continues below the incisor teeth to the midline, where it anastomoses with its fellow. In the canal the arteries supply the mandible, tooth sockets and teeth with branches entering the minute hole at the apex of the root to supply the pulp. The mental branch leaves the mental foramen, supplies the chin and anastomoses with the submental and inferior labial arteries. Near its origin the inferior alveolar artery has a lingual branch, which descends with the lingual nerve to supply the buccal mucous membrane.

Branches of the second part (10.79)

Deep temporal branches. Anterior and posterior, these branches ascend between the temporalis and bone, supplying mainly the former. They anastomose with the middle temporal artery. The anterior connects with the lacrimal by small branches perforating the zygomatic bone and greater wing of the sphenoid.

Pterygoid branches. Irregular in number and origin, these supply the pterygoid muscles.

Masseteric artery. This is small and with the masseteric nerve passes behind the tendon of temporalis through the mandibular incisure (notch) to the deep surface of masseter, in which it anastomoses with the masseteric branches of the facial and transverse facial arteries.

Buccal artery. Running obliquely forwards with the buccal nerve between the medial pterygoid and the attachment of the temporalis

it supplies the external surface of the buccinator (and through it the mucosa), anastomosing with branches of the facial and infraorbital arteries.

Branches of the third part

Posterior superior alveolar (dental) artery. Leaving the maxillary artery as it enters the pterygopalatine fossa, it descends on the maxilla's infratemporal surface. It then divides, some branches entering the alveolar canals to supply molar and premolar teeth and the maxillary sinus, others continuing over the alveolar process to supply the gingivae.

Infraorbital artery. Often arising with the posterior superior alveolar, it enters the orbit posteriorly through the inferior orbital fissure, to run in the infraorbital groove and canal with the infraorbital nerve, both emerging on the face via the infraorbital foramen, deep to the levator labii superioris. In the canal it has:

- *orbital branches*, which supply the rectus inferior, obliquus inferior and lacrimal sac
- *anterior superior alveolar (dental) branches*, which descend via the anterior alveolar canals to supply the upper incisor and canine teeth and the mucous membrane in the maxillary sinus.

On the face some branches ascend to the medial canthus and lacrimal sac, anastomosing with the terminal branches of the facial; others anastomose with a dorsal nasal branch of the ophthalmic artery and some descend between the levator labii superioris and levator anguli oris, anastomosing with the facial, transverse facial and buccal arteries.

The remaining branches arise in the pterygopalatine fossa.

Greater (or descending) palatine artery. This artery and nerve descend in their palatine canal; the artery gives off two or three lesser palatine arteries, transmitted through lesser palatine canals to supply the soft palate and tonsil, anastomosing with the ascending palatine. The main vessel emerges on the palate's oral surface by the greater palatine foramen and runs in a curved groove near the alveolar border of the hard palate to the incisive canal; it ascends this canal and anastomoses with a branch of the sphenopalatine artery. It supplies the gingivae, palatine glands and mucous membrane.

Pharyngeal artery. Very small, runs back through the pharyngeal (palatovaginal) canal with the pharyngeal branch of the pterygopalatine ganglion; it supplies the mucosa of the nasal roof, the nasopharynx, sphenoidal air sinus and auditory tube.

Artery of the pterygoid canal. Frequently from the greater palatine, it passes back in the pterygoid canal with the corresponding nerve, supplying its walls and contents and the mucous membrane of the upper pharynx, pharyngotympanic tube and tympanic cavity.

Relations. The pharyngeal artery is medial, that of the pterygoid canal lateral and the trunk of the maxillary artery passes anterior to the pterygopalatine ganglion.

Sphenopalatine artery. The termination of the maxillary, it traverses the sphenopalatine foramen into the walls of the nasal cavity posterior in the superior meatus. Here its *posterior lateral nasal branches* ramify over the conchae and meatuses, anastomosing with the ethmoidal arteries and nasal branches of the greater palatine, supplying the frontal, maxillary, ethmoidal and sphenoidal sinuses. Crossing anteriorly on the inferior sphenoid surface, the artery ends on the nasal septum as the *posterior septal branches*, which anastomose with the ethmoidal arteries; one branch descends on the vomer to the incisive canal to join the end of the greater palatine artery and septal branch of the superior labial.
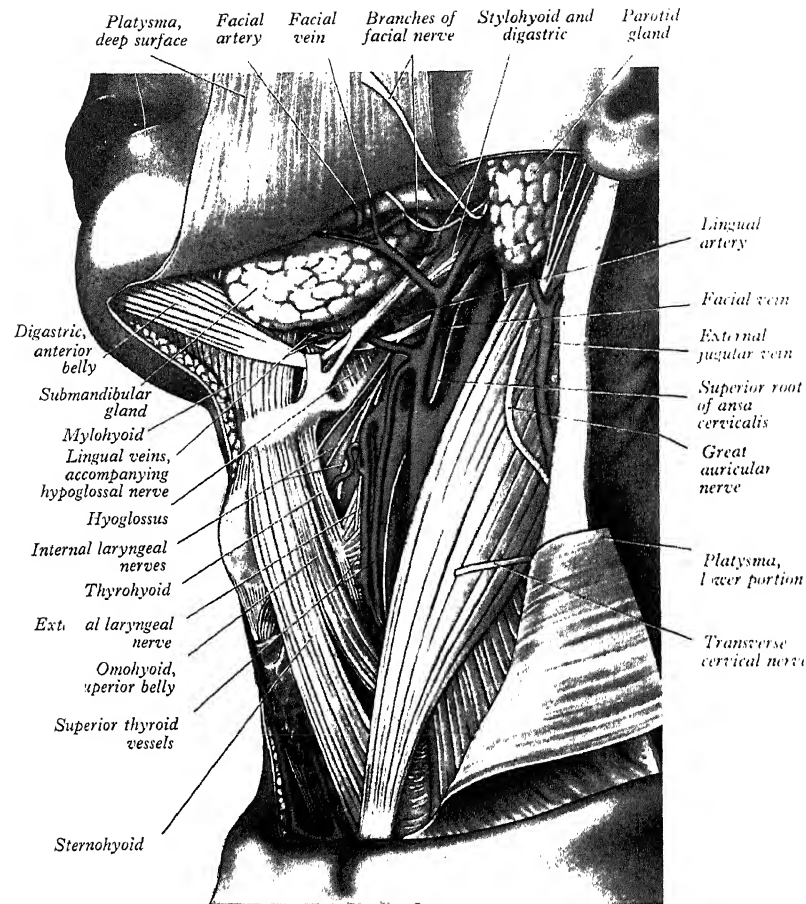
Collateral circulation

Collateral circulation, after interruption of one common carotid, is often established by the connections across the midline between the carotids, intra- and extracranial, and by enlargement of the subclavian branches. Chief extracranial connections are between superior and inferior thyroid arteries, the deep cervical and the descending branch of the occipital; the vertebral artery substitutes for the internal carotid in the cranium. Nevertheless symptoms of cerebral disturbance supervene in about 25% of cases.

After interruption of the *external* carotid, circulation is maintained by anastomoses between most of its large branches (facial, lingual, superior thyroid, occipital) and their fellows, by their anastomoses with branches of the internal carotid and of the occipital with branches of the subclavian, etc.

Anterolaterally the neck (10.80, 81) presents a somewhat quadrilateral area, limited **above** by the base of the mandible and a line continued from its angle to the mastoid process, **below** by the clavicle's upper border, **in front** by the anterior median line, **behind** by the anterior margin of trapezius. This region is divided by the sternocleidomastoid, ascending obliquely from the sternum and clavicle to the mastoid process and occipital bone. The area anterior to this is the *anterior triangle* and that behind it the *posterior triangle*. While these triangles and their subdivisions are emphasized by some as being purely arbitrary because many major structures (arteries, veins, lymphatics, nerves, some viscera) transgress their boundaries without interruption, nevertheless they have a topographical value in description. However, two further points should be made. Some of their subdivisions are easily identified by inspection and palpation and provide invaluable assistance in surface anatomical and clinical examination (see below). As the neck has a roughly cylindrical form, crossed obliquely by the sternocleidomastoid, the
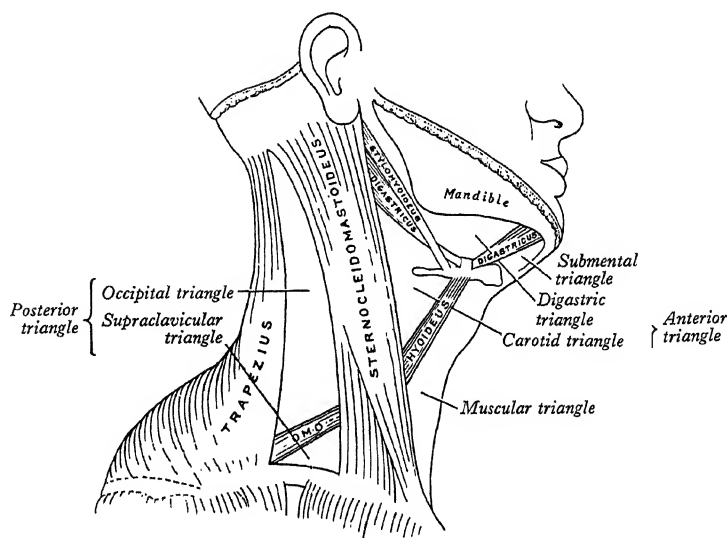
10.80 The triangles of the right side of the neck: a highly schematic two dimensional representation of what in reality are non-planar trigones distributed over a waisted column. Submandibular would be an alternative name for digastric.

Platysma, deep surface   *Facial artery*   *Facial vein*   *Branches of facial nerve*   *Stylohyoid and digastric*   *Parotid gland*

Lingual artery

Facial vein

External jugular vein

Superior root of ansa cervicalis

Great auricular nerve

Platysma, lower portion

Transverse cervical nerve

Digastric, anterior belly

Submandibular gland

Mylohyoid

Lingual veins, accompanying hypoglossal nerve

Hyoglossus

Internal laryngeal nerves

Thyrohyoid

External laryngeal nerve

Omohyoid, superior belly

Superior thyroid vessels

Sternohyoid

10.81 Dissection of the left anterior triangle. The platysma has been divided transversely; its upper part has been turned upwards on to the face, its lower part turned backwards, exposing the lower part of the sternocleidomastoid. Dominating the centre of the illustration is the carotid triangle, with many of its contents and surrounding structures.

names anterior and posterior are not particularly apt; the triangles are not plane (and coplanar as represented in a two-dimensional diagram such as **10.80**) but both are spiralized regions (trigones) on the surface of the column.

ANTERIOR CERVICAL TRIANGLE

This is bounded anteriorly by the median line, and posteriorly by the anterior margin of the sternocleidomastoid, its base being the inferior mandibular border and its mastoid extension noted above; its apex is at the manubrium. It may be subdivided into muscular, carotid, digastric and submental triangles.

Muscular triangle

The muscular triangle is bounded by the median line from the hyoid bone to the sternum, inferoposteriorly by the anterior margin of the sternocleidomastoid and posterosuperiorly by the superior belly of the omohyoid.

Carotid triangle

The carotid triangle is limited posteriorly by the sternocleidomastoid, antero-inferiorly by the superior belly of the omohyoid and superiorly by the stylohyoid and posterior belly of the digastric; in the living, except the obese, the triangle is usually a small visible triangular depression, sometimes best seen with the head and cervical vertebral column slightly extended and the head contralaterally rotated. Often the latter position is quite unnecessary; judicious oblique lighting (window or lamp) throws the hollow into relief.

It is covered by the skin, superficial fascia, platysma and deep fascia containing branches of facial and cutaneous cervical nerves. The hyoid bone forms its anterior angle and adjacent floor; its position can be located immediately on simple inspection, verified by palpation. Parts of thyrohyoid, hyoglossus and inferior and middle pharyngeal constrictors form its floor. It contains the upper part of the common carotid and its division into external and internal carotid

arteries, overlapped by the anterior margin of the sternocleidomastoid; the external carotid is first anteromedial, then anterior to the internal. Branches of the external carotid are also encountered: the superior thyroid runs antero-inferiorly, the lingual anteriorly with its upward loop, the facial anterosuperiorly, the occipital posterosuperiorly and the ascending pharyngeal medial to the internal carotid. Massive arterial pulsation greets the examining finger. The veins correspond to the branches of the external carotid artery: superior thyroid, lingual, facial, ascending pharyngeal and sometimes the occipital, all ending in the internal jugular vein. The hypoglossal nerve crosses both carotid arteries, curving round the origin of the lower sternocleidomastoid branch of the occipital, where the superior root of the ansa cervicalis leaves it, descending anteriorly in the carotid sheath. Medial to the external carotid, below the hyoid bone, is the internal laryngeal nerve and, below this, the external laryngeal. Many structures in this region, such as all or part of the internal jugular vein, associated deep

cervical lymph nodes, vagus nerve, etc., may be variably obscured by the sternocleidomastoid and, pedantically, are thus 'outside the triangle'; much more importantly, their location is obvious during clinical examination.

Digastric triangle

The digastric triangle is bordered above by the base of the mandible (and its projection to the mastoid process), posteroinferiorly by the posterior belly of the digastric and stylohyoid and anteroinferiorly by the anterior belly of digastric. It is covered by the skin, superficial fascia, platysma and deep fascia, in which are branches of facial and transverse cutaneous cervical nerves. Its floor is formed by the mylohyoid and hyoglossus. Its anterior region contains the submandibular gland, superficial to which is the facial vein and deep to it the facial artery, crossing the lower border of the mandible at the anterior edge of the masseter; on the mylohyoid are the submental artery and mylohyoid artery and nerve. Variably related to the submandibular gland are the submandibular lymph nodes (p. 1612). Its posterior region contains the lower part of the parotid gland; the external carotid, passing deep to the stylohyoid, curves above the muscle and overlaps its superficial surface where it ascends deep to the parotid gland to enter it. The external carotid, which is superficial to the internal carotid, crosses it posterolaterally; deeper and separated from the external carotid by styloglossus, stylopharyngeus and the glossopharyngeal nerve, are the internal carotid artery, internal jugular vein and vagus nerve.

Submental triangle

The submental triangle, unpaired, is demarcated by both digastric muscles (anterior bellies); its apex is at the chin, its base the body of the hyoid and its floor

the mylohyoid muscles. It contains lymph nodes and small veins uniting to form the anterior jugular.

POSTERIOR CERVICAL TRIANGLE

The posterior triangle is delimited anteriorly by the sternocleidomastoid, posteriorly by the anterior edge of trapezius, inferiorly by the middle third of the clavicle; its apex is between the attachments of the sternocleidomastoid and trapezius to the occiput and is often blunted, the 'triangle' becoming quadrilateral. It is crossed, about 2.5 cm above the clavicle, by the inferior belly of the omohyoid, which divides it into occipital and supraclavicular triangles.

Occipital triangle

The occipital triangle, the upper, larger part of the posterior triangle, has the same borders, except below where its limit is the omohyoid. Its floor is, from above down: splenius capitis, levator scapulae, and scaleni medius and posterior. (Sometimes semispinalis capitis appears at the apex.) It is covered by the skin, superficial and deep fasciae and below by the platysma. The accessory nerve pierces the sternocleidomastoid and crosses on the levator scapulae obliquely down and back to the deep surface of the trapezius; cutaneous and muscular branches of the cervical plexus emerge at the posterior border of the sternocleidomastoid; below, supraclavicular nerves, transverse cervical vessels and the uppermost part of the brachial plexus cross the triangle. Lymph nodes are arranged along the posterior border of the sternocleidomastoid from the mastoid process to the root of the neck.

Supraclavicular triangle

The supraclavicular triangle, the lower, smaller division, is bounded like the pos-

terior triangle, except above where the omohyoid limits it. It corresponds in the living neck with the lower part of the deep, prominent hollow, the greater supraclavicular fossa (colloquially 'the salt cellar'). Its floor contains the first rib, scalenus medius and the first slip of serratus anterior. Its size varies with the extent of the clavicular attachments of the sternocleidomastoid and trapezius and also the level of the inferior belly of the omohyoid. The triangle is covered by the skin, superficial and deep fasciae and platysma and crossed by the supraclavicular nerves. Just above clavicular level the third part of the subclavian artery curves inferolaterally from the lateral margin of the scalenus anterior, across the first rib to the axilla. The subclavian vein is behind the clavicle and is not usually in the triangle; but it may rise as high as the artery and even accompany it behind scalenus anterior. The brachial plexus is partly above, partly behind the artery and closely related to it. The trunks of the brachial plexus may easily be palpated here, the neck being contralaterally flexed and the examining finger drawn across the trunks at right angles to their length. With the musculature relaxed, pulsation of the subclavian artery may be felt or the arterial flow controlled by retroclavicular compression against the first rib. The suprascapular vessels pass transversely behind the clavicle; at a higher level are the transverse cervical artery and vein. The external jugular vein descends behind the posterior border of the sternocleidomastoid to end in the subclavian vein; it receives the transverse cervical and suprascapular veins, which form a plexus in front of the third part of the subclavian artery; occasionally it is joined by a small vein crossing the clavicle anteriorly from the cephalic vein. The nerve to the subclavius also crosses this triangle and some lymph nodes are contained in it.

INTERNAL CAROTID ARTERY

The internal carotid artery (10.82–89) supplies most of the ipsilateral cerebral hemisphere, eye and accessory organs, forehead and, in part, the nose. From the carotid bifurcation, where it usually has a carotid sinus (p. 1514), it ascends to the cranial base, enters the cranial cavity by the carotid canal and turns anteriorly through the cavernous sinus in the carotid groove on the side of the sphenoid body, ending below the anterior perforated substance by division into the anterior and middle cerebral arteries.

It may be divided conveniently into cervical, petrous, cavernous and cerebral parts. In the broadest outline its course is:

- **vertically upwards** in the neck
- curving **horizontally forwards** and **medially** in the petrous carotid canal
- **upwards** in the upper foramen lacerum
- **horizontally forwards** in the cavernous sinus
- **vertically upwards** medial to the anterior clinoid process
- looping a short distance **backwards** and **upwards** to its terminal division.

Cervical part

This section begins at the carotid bifurcation and ascends in front of the upper three cervical transverse processes to the inferior aperture of the carotid canal in the petrous temporal bone. It is superficial at first in the carotid triangle, then passes deeper, medial to the posterior belly of the digastric. Except near the skull, the internal jugular vein and vagus nerve are lateral; the external carotid is first anteromedial but then curves back to become superficial. The artery has many other relations. **Posteriorly** it adjoins the longus capitis, with the superior cervical sympathetic ganglion between them and the superior laryngeal nerve crossing obliquely behind it. **Medial** is the pharyngeal wall separated by fat and pharyngeal veins from the ascending pharyngeal artery and superior laryngeal nerve. **Anterolaterally** the artery is covered by the sternocleidomastoid; **below the** digastric, the hypoglossal nerve and superior root of the ansa cervicalis and the lingual and facial veins are superficial. **At the level of** the digastric it is crossed by the stylohyoid muscle and the occipital and posterior auricular arteries. **Above** the digastric it is separated from the external carotid by the styloid process, styloglossus and stylopharyngeus, glossopharyngeal nerve, vagal pharyngeal branch

10.82 Internal carotid arteriogram (right): lateral view, in adult male of 33 years. The following can be identified: parts of the internal carotid artery (and individual vessels): 1. Cervical. 2. Intrapetrous. 3. Cavernous. 4. Terminal. 5. Ophthalmic artery. 6. Anterior cerebral artery. 7. Branches of middle cerebral artery. Note the absence of radio-opaque injectant from the cerebellar vessels.

and the deeper part of the parotid gland. **At the base of the skull** the glossopharyngeal, vagus, accessory and hypoglossal nerves are between the internal carotid artery and the internal jugular vein, which here has become posterior.

Petrous part

The artery at first ascends in the carotid canal, curves anteromedially and then superomedially above the cartilage filling the foramen lacerum, to enter the cranial cavity, passing between the lingula and petrosal process. It is at first anterior to the cochlea and tympanic cavity, separated from the latter and the pharyngotympanic tube by a thin, bony lamella, cribriform in the young, partly absorbed in old age; anterior to this it is separated from the trigeminal ganglion by the thin roof of the carotid canal, often deficient. The artery is surrounded by a venous plexus and the carotid autonomic plexus derived from the internal carotid branch of the superior cervical ganglion.

Cavernous part

In the cavernous sinus the artery is covered by lining endothelium of the veins. It ascends to the posterior clinoid process, turns anteriorly to the side of the sphenoid and again curves up medial to the anterior clinoid process, emerging through the dural roof of the sinus; occasionally the two clinoid processes form a ring round the artery, which is also surrounded by a sympathetic plexus; the oculomotor, trochlear, ophthalmic and abducens nerves are lateral to it.

Cerebral part

Having traversed the dura mater the artery turns back below the optic nerve, passing between this and the oculomotor nerve to the anterior perforated substance at the medial end of the lateral cerebral sulcus, where it divides into anterior and middle cerebral arteries.

Variations. The length of the artery varies with the length of the neck and the point of carotid bifurcation. It may arise from the aortic arch and then be medial to the external carotid as far as the larynx but there crossing behind it. Its cervical part is normally straight but on occasion may be very tortuous, being nearer to the pharynx than usual and very near the tonsil. Its absence has also been recorded.

Surface anatomy. The internal carotid corresponds in position to a broad line from the termination of the common carotid to the back of the mandibular neck (**10.75**).
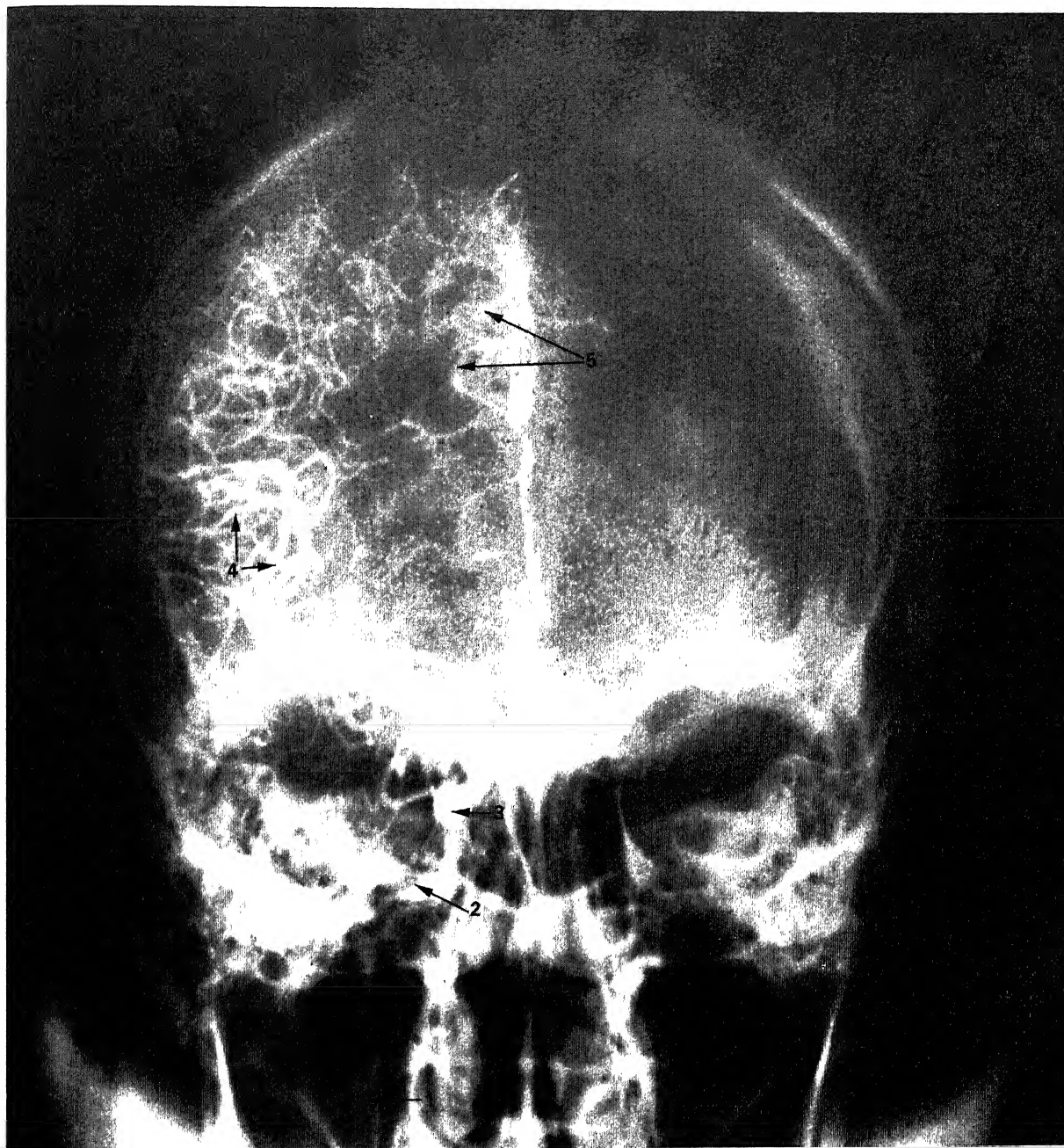
10.83 Internal carotid arteriogram (right): anteroposterior view of same subject as **10.82**. Parts of the internal carotid artery: 1. Cervical. 2. Intra-petrous. 3. Cavernous. 4. Branches of middle cerebral artery. 5. Branches of anterior cerebral artery. Note the lack of contrast medium on the left side.

Branches. The cervical part has no branches. Those from the other parts are:

From the petrous part

- Caroticotympanic
- Pterygoid

From the cavernous part

- Cavernous
- Hypophyseal
- Meningeal

From the cerebral part

- Ophthalmic
- Anterior cerebral
- Middle cerebral
- Posterior communicating
- Anterior choroid.

Caroticotympanic artery. Small, occasionally double, it enters the tympanic cavity by a foramen in the carotid canal, anastomosing with the anterior tympanic branch of the maxillary artery and the stylomastoid artery.

Pterygoid artery. Inconstant, it enters the pterygoid canal with the nerve of the same name, anastomosing with a (recurrent) branch of the greater palatine artery.

Cavernous branches. Numbers of these small vessels supply the trigeminal ganglion, walls of the cavernous and inferior petrosal sinuses and contained nerves. Some anastomose with middle meningeal branches.

**Hypophyseal branches.** Small but numerous, they are important vessels (for details see p. 1887).

1525
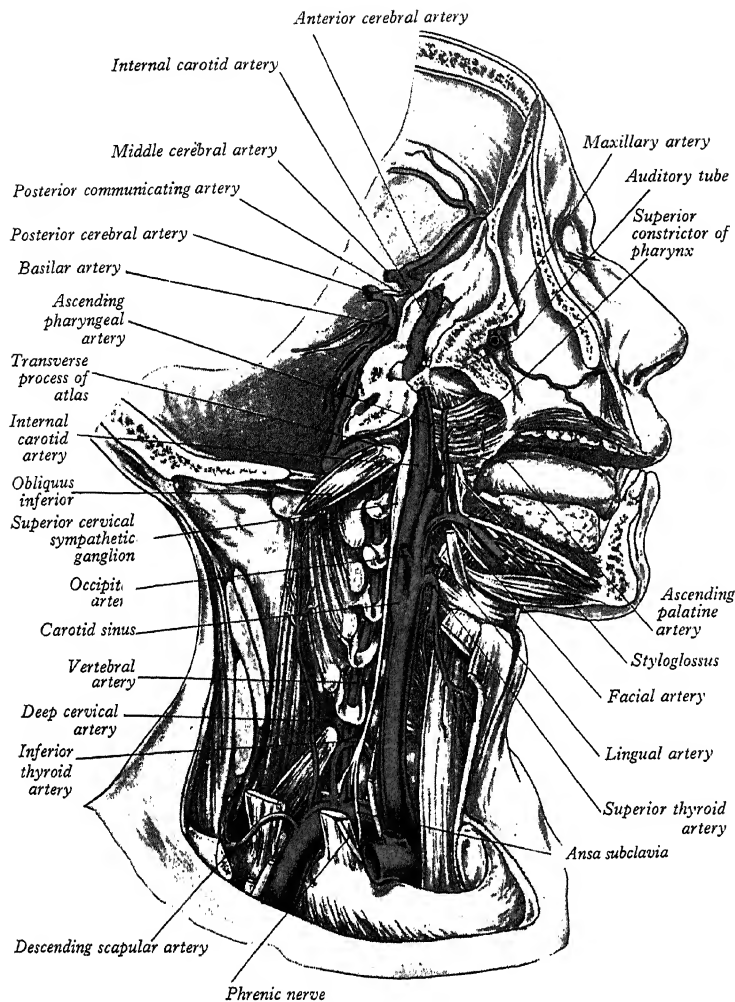
10.84 Dissection to show the course of the right vertebral and internal carotid arteries and some of their branches.

10.85 The ophthalmic artery and its branches in the right orbit, as seen from above.

Meningeal branch. This is minute and passes over the lesser sphenoid wing to supply the dura mater and bone in the anterior cranial fossa; it anastomoses with a meningeal branch of the posterior ethmoidal artery.

Ophthalmic artery (10.85). It leaves the internal carotid as it quits the cavernous sinus medial to the anterior clinoid process; it enters the orbit by the optic canal, inferolateral to the optic nerve; for a short distance it is then lateral to the nerve, medial to the oculomotor and abducens nerves, ciliary ganglion and rectus lateralis. It crosses between the optic nerve and rectus superior to the medial orbital wall, runs between the obliquus superior and the rectus medialis to the medial end of the upper eyelid, dividing into *supratrochlear* and *dorsal nasal branches*. As it crosses the optic nerve with the nasociliary nerve it is separated from the frontal nerve by the rectus superior and levator palpebrae superioris; its terminal branch accompanies the infratrochlear nerve. In about 15% of subjects the ophthalmic artery is below the optic nerve. Its branches are as follows:

Central artery of the retina. A first and small branch, it begins below the optic nerve. For a short distance it is in the nerve's dural sheath; about 1.25 cm behind the eye it enters the nerve's inferomedial surface and runs to the retina along its axis. Its distribution is described on page 1347.

Lacrimal artery. Leaving the ophthalmic near its exit from the optic canal, it is a large branch, sometimes arising before the ophthalmic enters the orbit; a branch of the middle meningeal artery (p. 1520) may replace it. It accompanies the lacrimal nerve along the upper border of the rectus lateralis, supplying the lacrimal gland, after traversing which it ends in the eyelids and conjunctiva as *lateral*
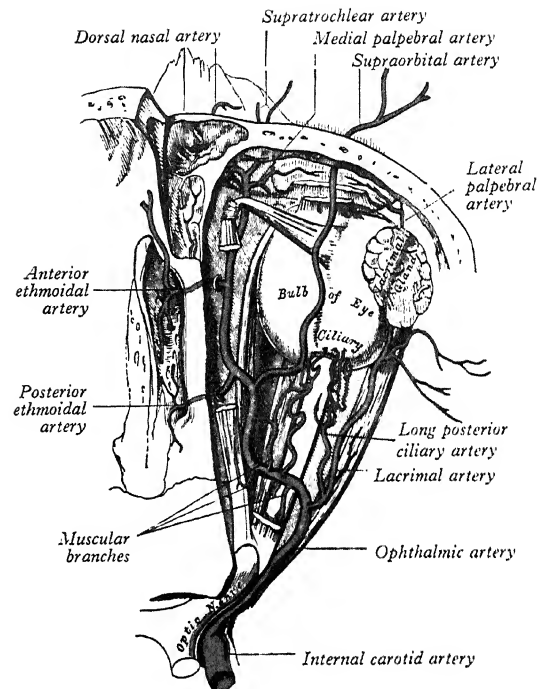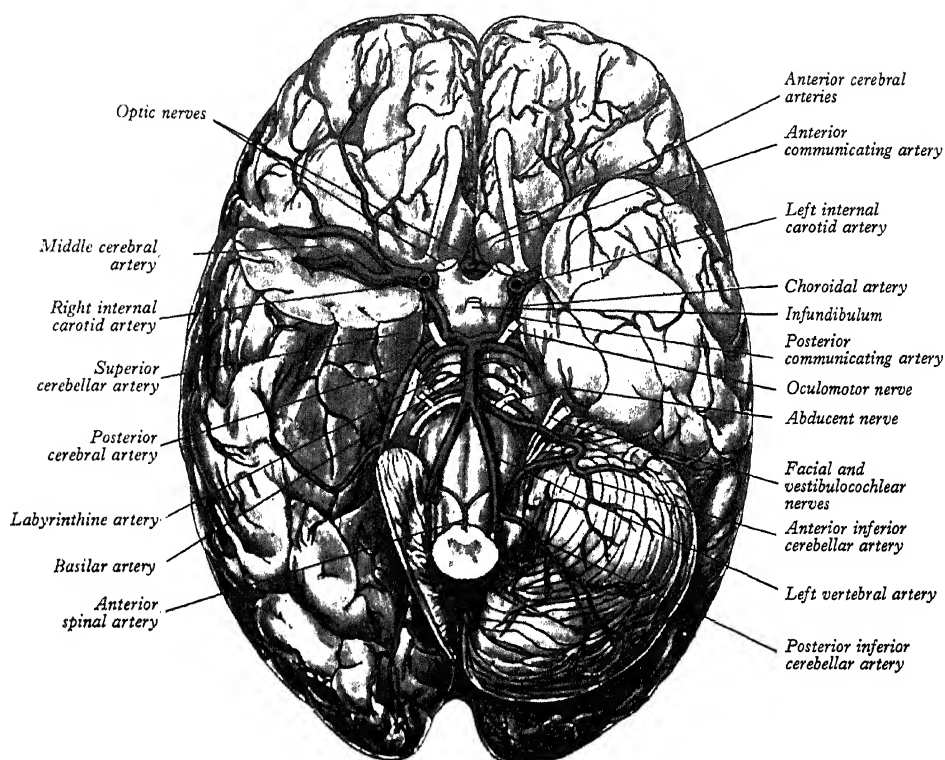
palpebral arteries running medially in the upper and lower lids to anastomose with the medial palpebral arteries. The lacrimal artery gives off one or two *zygomatic branches*: one reaches the temporal fossa via the zygomaticotemporal foramen, anastomosing with the deep temporal arteries; another reaches the cheek by the zygomaticofacial foramen, anastomosing with transverse facial and zygomatico-orbital arteries. A *recurrent meningeal branch* passes back via the lateral part of the superior orbital fissure to anastomose with a middle meningeal branch; enlargement of this anastomosis may provide an alternative lacrimal artery.

Muscular branches. These frequently spring from a common trunk but form superior and inferior groups, most accompanying branches of the oculomotor nerve. The inferior, more constant, contains most of the anterior ciliary arteries. Other muscular vessels branch from the lacrimal and supraorbital or the trunk of the ophthalmic artery.

Ciliary arteries. They are divisible into three groups: long and short posterior and anterior. *Long posterior ciliary arteries*, usually two, pierce the sclera near the optic nerve (p. 1132). About seven *short posterior ciliary arteries* pass around the optic nerve to the eyeball; dividing into 15–20 branches, they pierce the sclera around the optic nerve to supply the choroid and the ciliary processes. At the optic disc they anastomose with twigs of the central retinal artery and at the ora serrata with the long posterior and anterior ciliary arteries. *Anterior ciliary arteries* arise from muscular branches of the ophthalmic; reaching the eyeball on tendons of the recti to form a circumcorneal subconjunctival vascular zone, they pierce the sclera near the sclerocorneal junction and end in the greater arterial circle of the iris (p. 1132).

Supraorbital artery. Leaving the ophthalmic where it crosses the optic nerve, it ascends medial to the rectus superior and levator palpebrae superioris, meets the supraorbital nerve and runs with it between the periosteum and levator palpebrae superioris to the supraorbital foramen or notch; traversing this it divides into superficial and deep branches, supplying the skin, muscles and frontal periosteum, anastomosing with the supratrochlear artery, frontal branch of the superficial temporal and its fellow. It supplies the rectus superior and levator palpebrae and sends a branch across the trochlea to the medial canthus. At the supraorbital margin it often sends a branch to the diploe of the frontal bone and may also supply the mucoperiosteum in the frontal sinus.

Posterior ethmoidal artery. Entering the posterior ethmoidal canal,

1526

Optic nerves

Middle cerebral artery

Right internal carotid artery

Superior cerebellar artery

Posterior cerebral artery

Labyrinthine artery

Basilar artery

Anterior spinal artery

Anterior cerebral arteries

Anterior communicating artery

Left internal carotid artery

Choroidal artery

Infundibulum

Posterior communicating artery

Oculomotor nerve

Abducent nerve

Facial and vestibulocochlear nerves

Anterior inferior cerebellar artery

Left vertebral artery

Posterior inferior cerebellar artery

10.86 The arteries at the base of the brain. The right temporal pole and most of the right hemisphere of the cerebellum have been removed. Variations in the pattern of these vessels are common.

it supplies the posterior ethmoidal air sinuses, enters the cranium, sends a meningeal branch to the dura mater and nasal branches descending into the nasal cavity via the cribriform plate, to anastomose with the sphenopalatine branches supplying bone.

Anterior ethmoidal artery. Together, artery and nerve traverse their canal, the artery supplying anterior and middle ethmoidal and frontal air sinuses and, entering the cranium, giving a meningeal branch to the dura mater and nasal branches descending into the nasal cavity with the anterior ethmoidal nerve; they run in a groove on the deep surface of the nasal bone to supply the lateral nasal wall and septum; a terminal branch appears on the nose between the nasal bone and the upper nasal cartilage. Angiographic studies (Kuru 1967) show the meningeal branch extending to the falx; Müller (1977) has confirmed this in fetal and adult material; he also derives such *'falciate arteries'* from the recurrent meningeal branch of the lacrimal artery.

Meningeal branch. A small artery passing back by the superior orbital fissure to the middle cranial fossa, it anastomoses with the

middle and accessory meningeal arteries, supplying bone.

Medial palpebral arteries. Superior and inferior, they leave the ophthalmic below the trochlea, descending behind the lacrimal sac to enter the lids, where each divides into two branches coursing laterally along the tarsal edges, to form the superior and inferior arches, completed by anastomoses with branches of the supraorbital and zygomatico-orbital (superior arch) and palpebral branches of the lacrimal (both arches); the inferior arch also links with the facial artery, thus supplying the mucosa of the nasolacrimal duct.

Supratrochlear artery. A terminal branch of the ophthalmic, it leaves the orbit superomedially with the supratrochlear nerve, ascending on the forehead to supply the skin, muscles and pericranium, anastomosing with the supraorbital artery and with its fellow.
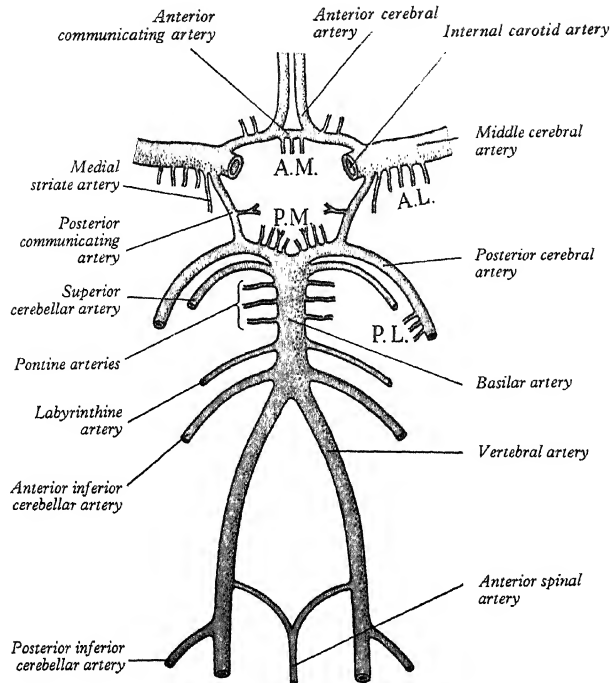
Dorsal nasal artery. The other terminal branch, it emerges from the orbit between the trochlea and medial palpebral ligament, gives a branch to the upper lacrimal sac and divides; one branch joins the terminal part of the facial artery, the other runs along the dorsum
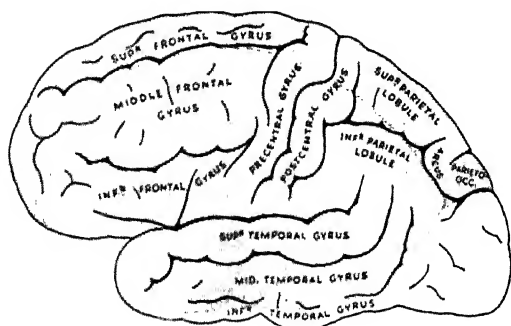
10.87A The lateral surface of the left cerebral hemisphere, showing the areas supplied by the cerebral arteries. In this and the next figure the area supplied by the anterior cerebral artery is coloured blue, that by the middle cerebral artery pink and that by the posterior cerebral artery is yellow.
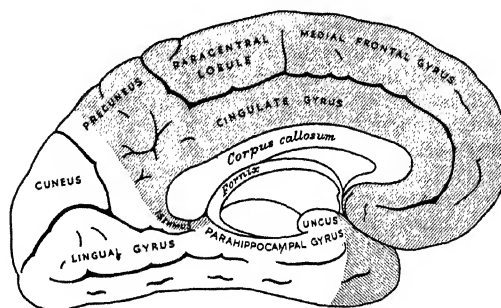
10.87B The medial surface of the left cerebral hemisphere, showing the areas supplied by the cerebral arteries (see description of 10.86).

of the nose supplying its exterior and joining its fellow and lateral nasal branch of the facial.

Anterior cerebral artery (10.86–89). The smaller terminal branch of the internal carotid, it starts at the medial end of the stem of the lateral cerebral sulcus and passes anteromedially above the optic nerve to the longitudinal fissure, where it connects with its fellow by a short transverse anterior communicating artery. The two arteries thence travel together in the fissure, curving round the genu of the corpus callosum and back along its upper surface to its posterior end, where they anastomose with posterior cerebral arteries. Occasionally they are a single vessel. There are central and cortical branches.

Anterior communicating artery. With an average length of 4 mm, it connects anterior cerebral arteries across the anterior end of the longitudinal fissure; it may be double. It has a few anteromedial central branches. According to Crowell and Morawetz (1977) its branches, from three to 13, supply the optic chiasma, lamina terminalis, hypothalamus, paraolfactory areas, fornix (anterior columns) and cingulate gyrus.

Central branches. These arise from the commencement of the anterior cerebral, entering the anterior perforated substance and lamina terminalis to supply the rostrum of the corpus callosum, septum pellucidum, the anterior part of the putamen of the lentiform nucleus and the head of the caudate nucleus. *Cortical branches* are named by distribution: two or three *orbital branches* ramify on the frontal lobe's orbital surface, supplying the olfactory lobe, gyrus rectus and medial orbital gyrus; *frontal branches* supply the corpus callosum, cingulate gyrus, medial frontal gyrus and paracentral lobule, sending twigs over the hemisphere's superomedial border to the superior and middle frontal gyri and upper part of the precentral gyrus (including the 'leg area' of the motor cortex, p. 1164); *parietal branches* supply the precuneus and the adjacent lateral surface.

Middle cerebral artery (10.86–89). The larger terminal branch of the internal carotid, it runs first in the lateral cerebral sulcus, then posterosuperiorly on the insula, dividing into branches distributed to this and the adjacent lateral cerebral surface. Its *central branches* are small and from its commencement they enter the anterior

perforated substance, arranged in two sets: *medial striate arteries* ascend through the lentiform nucleus to supply it, the caudate nucleus and the internal capsule; *lateral striate arteries* ascend over the lower lateral aspect of the lentiform nucleus (in the external capsule) and turn medially to traverse it and the internal capsule to supply the caudate nucleus. One lateral branch, usually the largest, was termed by Charcot the 'artery of cerebral haemorrhage'. *Cortical branches* supply orbital branches to the inferior frontal gyrus and the lateral orbital surface of the frontal lobe; frontal branches supply the precentral, middle and inferior frontal gyri; two *parietal branches* are distributed to the postcentral gyrus, the lower part of the superior parietal lobule and the whole inferior parietal lobule. Two or three *temporal branches* supply the lateral surface of the temporal lobe. Cortical branches of the middle cerebral thus supply all the motor area (excluding the leg), the corresponding somaesthetic area (p. 1116) and the auditory area (p. 1204).

Posterior communicating artery (10.86, 88, 89). This runs back from the internal carotid above the oculomotor nerve, anastomosing with the posterior cerebral, a basilar branch. It is usually small but sometimes so large that the posterior cerebral appears to come from the internal carotid rather than basilar artery. It is often larger on one side. From its posterior half several small branches pierce the posterior perforated substance with others from the posterior cerebral to supply the medial thalamic surface and walls of the third ventricle (p. 1203).

Anterior choroidal artery. Small but constant, it leaves the internal carotid near its posterior communicating branch (Abbie 1933, 1934), passing back above the medial part of the uncus to cross inferior to the optic tract and reach and supply the crus cerebri. Turning laterally, it recrosses the optic tract, arrives lateral to the lateral geniculate body and supplies it with several branches. Finally it enters the inferior cornu of the lateral ventricle via the choroidal fissure to end in the choroidal plexus. It supplies: the globus pallidus, caudate nucleus and amygdaloid body, hypothalamus, tuber cinereum, red nucleus, substantia nigra, posterior limb of the internal capsule, the optic radiation, optic tract, hippocampus and the fimbria of the fornix.

Much of the brain is supplied by the two internal carotid arteries (p. 1523), and a central anastomosis, the Circle of Willis (also known as *circulus arteriosus*), exists between these and the two vertebral arteries (p. 1530) that supply the remainder. This 'circle', more polygonal than circular, is in the cisterna interpeduncularis, surrounding the optic chiasma, the neural infundibular stem of the hypophysis cerebri and other related neural structures in the interpeduncular fossa (10.88, 89). Anteriorly the anterior cerebral arteries (from the carotids) are joined by the anterior communicating artery; **posteriorly** the basilar artery (p. 1534) divides into two posterior cerebral arteries, each joined to the ipsilateral internal carotid by a posterior communicating artery (10.88).

Vessels of this 'circle' vary in calibre, being often partially developed, sometimes even absent. About 60% of circles display 'anomalies'; the above description applies to a minority.

Variations

Variations have been much studied, from Windle's account in 1888 of 200 specimens to that of Puchades-Orts et al (1976) in 62 dissections, the largest series being the 700 dissections of Fawcett and Blachford (1906) and Riggs and Rupp's (1963) 994 dissections. Fields et al (1965) have summarized such studies. Cerebral and communicating arteries, anterior and posterior, may all be absent, variably hypoplastic, double or even triple. In about 90% there is, nevertheless, a complete 'circular' channel but in most one vessel is sufficiently narrowed to reduce its role as a collateral route. The haemodynamic 'balance' is usually disturbed by variation in the calibre of communicating arteries, often with variation in the segments of anterior and posterior cerebral arteries extending from their origins to their junctions with the corresponding communicating arteries. This is especially true in the case of the posterior cerebral artery and its anastomosis with the posterior communicating artery. Commonly the precommunicating part of the posterior cerebral artery has a diameter larger than the posterior communicating artery; in this case the blood supply to the occipital lobes is mainly from the vertebrobasilar system. Less commonly the diameter of the precommunicating part of the posterior cerebral artery is smaller than that of the posterior communicating artery, in which case the blood supply to the occipital lobes is mainly from the internal carotids via the posterior communicating arteries (Van Overbeeke et al 1991). The latter arrangement, whose frequency ranges according to different studies from 6% (McCormick 1969) to 40% (Zeal and Rhoton 1978), is sometimes referred to as the 'embryonic configuration' (as opposed to the standard 'adult configuration'), and according to Abbie (1933), Williams (1936) and Kaplan (1956) is accounted for by the ontogenetic and phylogenetic association of posterior cerebral and internal carotid arteries. However, a recent study has shown that the 'embryonic configuration' is not more common in human fetuses than in adults (Van Overbeeke et al 1991). Anterior in the arterial circle, agenesis or hypoplasia of the initial anterior cerebral segment is more frequent than anomalies in the anterior communicating, and hence a commoner cause of defective circulation. Angiographic evidence indicates such defective or absent circulation in about a third of individuals (Sedzmir 1959); existence of an effective arterial circle can never be assumed and surgical procedures involving its 'feeders' must be preceded by angiography. Radio-opaque substances may be injected into the internal carotid or vertebral arteries in the neck for radiography of the condition of their intracranial branches (10.82, 83, 93, 94).

Further details of the distribution of cerebral arteries and veins appear on pages 1218 to 1220 and of intracranial venous sinuses on pages 1582 to 1589.

The stem artery of the upper limb is single as far as the elbow, but its name changes in the regions traversed. From its origin to the outer border of the first rib it is *subclavian*; thence to the tendon of teres major it is *axillary*; and from this to its division at the elbow it is *brachial*.

The right subclavian arises from the brachiocephalic trunk, the left from the aortic arch. For description, each is divided into a *first part*, from its origin to the medial border of the scalenus anterior, a *second part* behind this muscle and a *third part* from the muscle's lateral margin to the first rib's outer border, where the artery becomes axillary. Each subclavian artery arches over the cervical pleura and pulmonary apex. Their first parts differ, the second and third parts are almost identical.

First part of right subclavian artery

The right subclavian, branching from the brachiocephalic trunk behind the upper border of the right sternoclavicular joint, passes superolaterally to the medial margin of the scalenus anterior (10.66, 84, 90). It ascends about 2 cm above the clavicle but this varies.

Relations. The artery is deep to the skin, superficial fascia, platysma, anterior supraclavicular nerves, deep fascia, clavicular attachment of the sternocleidomastoid, sternohyoid and sternothyroid. It is at first behind the right common carotid's origin; more laterally it is crossed by the vagus n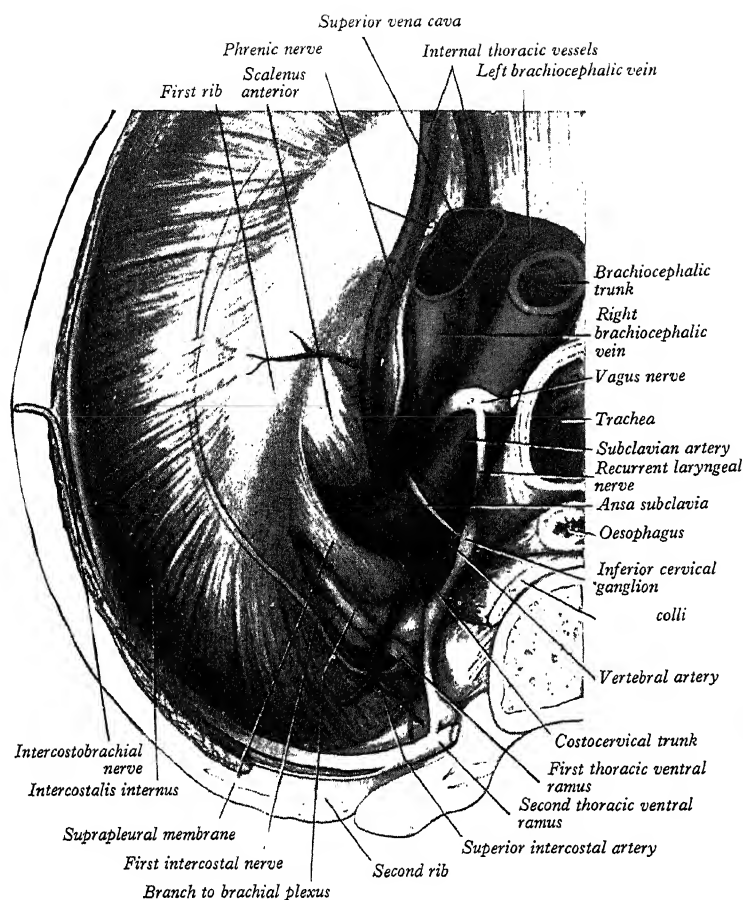erve, the cardiac branches of the vagus and the sympathetic chain and by internal jugular and vertebral veins; the subclavian sympathetic loop encircles it. The anterior jugular vein diverges laterally in front of it, separated by the sternohyoid and sternothyroid. Below and behind the artery are the pleura and pulmonary apex but separated by the suprapleural membrane (p. 1663), the ansa subclavia, an accessory vertebral vein (p. 1580) and the right recurrent laryngeal nerve (curving round inferoposterior to the vessel).

First part of left subclavian artery

This springs from the aortic arch, behind the left common carotid, level with the disc between the third and fourth thoracic vertebrae; it ascends into the neck, then arches laterally to the medial border of the scalenus anterior (10.48, 66, 91).

Relations. In the *thorax* it is related, **anteriorly** to the left common carotid artery and left brachiocephalic vein, separated by the left vagus, cardiac (p. 1253) and phrenic nerves. Superficial to these the anterior pulmonary margin, pleura, sternothyroid and sternohyoid are between the vessel and the upper left area of the manubrium sterni. **Posterior** are the left side of the oesophagus, the thoracic duct and longus colli; it is in contact posterolaterally with the left lung and pleura. **Medial** are the trachea, the left recurrent laryngeal nerve, oesophagus and thoracic duct. **Laterally** the artery grooves the mediastinal surface of the left lung and pleura which also encroach on its anterior and posterior aspects.

In the neck, near the medial border of the scalenus anterior, the artery is crossed anteriorly by the left phrenic nerve and the termination of the thoracic duct. Otherwise anterior relations are as

Superior vena cava
Phrenic nerve
Scalenus anterior
First rib
Internal thoracic vessels
Left brachiocephalic vein
Brachiocephalic trunk
Right brachiocephalic vein
Vagus nerve
Trachea
Subclavian artery
Recurrent laryngeal nerve
Ansa subclavia
Oesophagus
Inferior cervical ganglion
colli
Vertebral artery
Costocervical trunk
First thoracic ventral ramus
Second thoracic ventral ramus
Superior intercostal artery
Second rib
Intercostobrachial nerve
Intercostalis internus
Suprapleural membrane
First intercostal nerve
Branch to brachial plexus

10.90 Structures related to the right cervical pleura, as seen from below.

previously described for the first part of the right subclavian artery. Posteriorly and inferiorly, the relations of both vessels are identical but the left recurrent laryngeal nerve, medial to the left subclavian artery in the thorax, is not directly related to its cervical part.

Second part of subclavian artery

This is behind the scalenus anterior; it is short and the highest part of the vessel (**10.73, 92**).

Relations. Anterior are the skin, superficial fascia, platysma, deep cervical fascia, sternocleidomastoid and scalenus anterior; the right phrenic nerve is often described as separated from the second part by the scalenus anterior, but crossing the first part on the left; Qvist (1977) stated that both nerves are anterior to the muscle. Postero-inferior are the suprapleural membrane, pleura and lung and the lower trunk of the brachial plexus; superior are the upper and middle trunks of the plexus; the subclavian vein is antero-inferior, separated by the scalenus anterior (**10.92**).

Third part of subclavian artery

This descends laterally from the lateral margin of the scalenus anterior to the outer border of the first rib, where it becomes axillary; it is the most superficial part of the artery and lies partly in the supraclavicular triangle (p. 1523), where its pulsations may be felt and it may be compressed.

Relations. Anterior are the skin, superficial fascia, platysma, supraclavicular nerves and deep cervical fascia (**10.68, 92**). The external jugular vein crosses its medial end and here receives the suprascapular, transverse cervical and anterior jugular veins, together often forming a venous plexus. The nerve to the subclavius descends between the veins and the artery; the latter is terminally behind the clavicle and subclavius, where it is crossed by the suprascapular vessels. The subclavian vein is antero-inferior and the lower trunk of the brachial plexus is postero-inferior, between the artery and the

scalenus medius (and on the first rib). Superolateral are the upper and middle trunks of the brachial plexus (palpable here) and the inferior belly of the omohyoid. Inferior is the first rib.

Surface anatomy. The subclavian artery describes a broad line, convex superiorly, from the sternoclavicular joint to the midpoint of the clavicle (**10.75**).

Variations. The right subclavian may arise above or below sterno-clavicular level; it may be a separate aortic branch and be the first or last branch of the arch; when first, it is in the position of a brachiocephalic trunk and when last it arises from the arch's left end, ascending obliquely to the right behind the trachea, oesophagus and right common carotid to the first rib. In this case the proximal part of the artery represents a persistent part of the right dorsal aorta, the right fourth aortic arch taking no part in its formation (p. 1510); hence the right recurrent laryngeal nerve hooks round the common carotid, derived from the third arch. Sometimes, when the right subclavian is the last aortic branch, it passes between trachea and oesophagus. It may perforate the scalenus anterior; very rarely it passes anterior to it. Sometimes the subclavian vein accompanies the artery behind the scalenus anterior. The artery may ascend as high as 4 cm above the clavicle or it may reach only its upper border. The left subclavian is occasionally combined at its origin with the left common carotid.

Clinical anatomy. The third part of the subclavian artery is the most accessible. Since the line of the posterior border of the sterno-cleidomastoid approximates to the (deeper) lateral border of the scalenus anterior, the artery is just lateral to the former and, as noted, can be felt in the antero-inferior angle of the posterior triangle. It can only be effectively compressed against the first rib; with shoulder depressed, pressure is exerted down, back and medially in the angle between the sternocleidomastoid and clavicle. The palpable trunks of the brachial plexus may be injected with local anaesthetic allowing major surgical procedures to the arm.

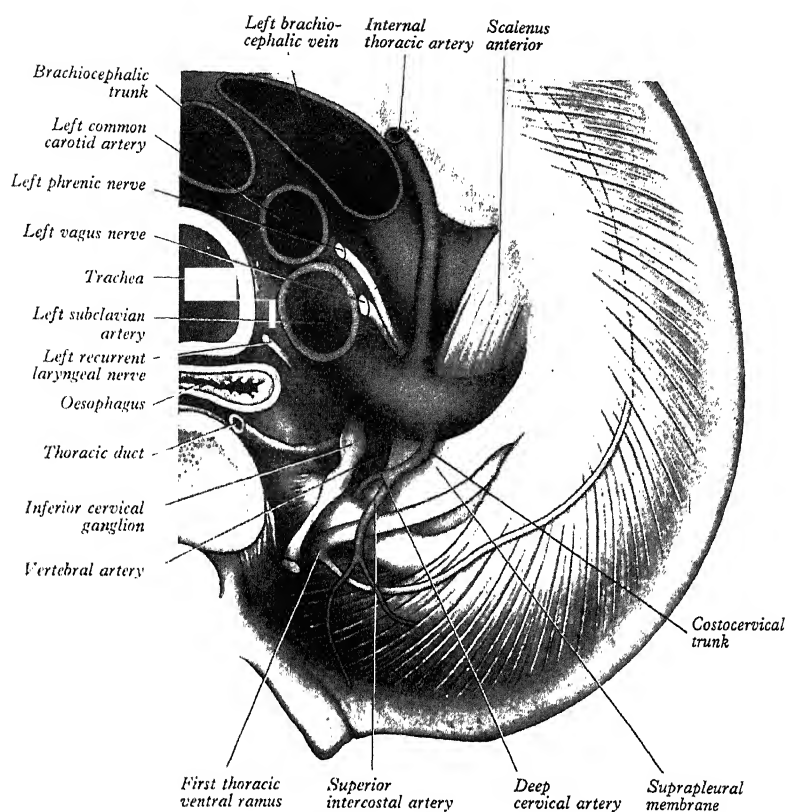## BRANCHES OF THE SUBCLAVIAN ARTERY

These branches are:

1. Vertebral
2. Internal thoracic
3. Thyrocervical
4. Costocervical
5. Dorsal scapular.

On the left all branches except the dorsal scapular arise from the first part; on the right the costocervical trunk usually springs from the second part. The origins of branches proceeding into the posterior triangle are variable but distributions are relatively constant.
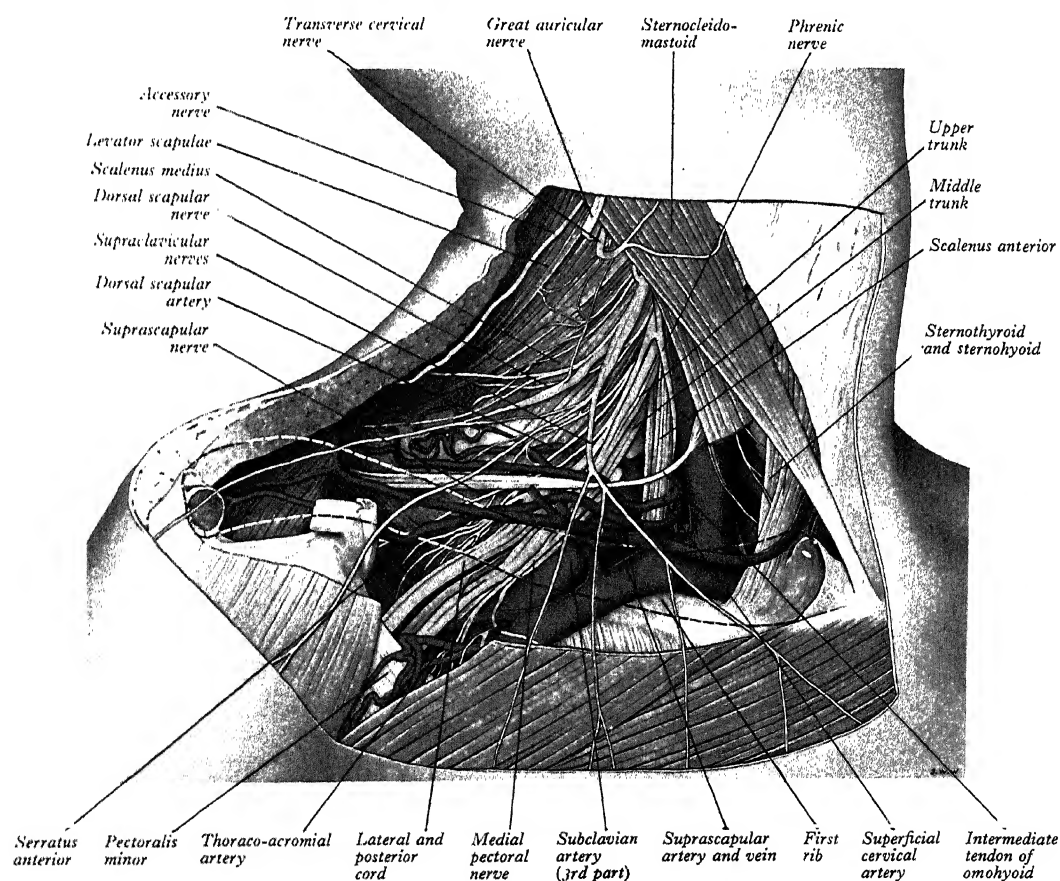
1. Vertebral artery

This artery arises from the superoposterior aspect of the subclavian, passes through the foramina of all cervical transverse processes except the seventh, curves medially behind the lateral mass of the atlas and then enters the cranium via the foramen magnum. At the lower pontine border it joins its fellow to form the basilar artery. Occasionally it may enter the bone at the fifth, fourth or seventh cervical transverse foramen (**10.83, 86, 88, 89, 90, 93, 94, 154**; p. 1510).

Relations. The *first part* ascends back between the longus colli and scalenus anterior, behind the common carotid artery and vertebral vein, and crossed by the inferior thyroid artery, and on the left also by the thoracic duct. **Posterior** are the seventh cervical transverse process, the stellate ganglion (**10.86, 89, 90, 91**) and ventral rami of the seventh and eighth cervical spinal nerves. The *second part* ascends through the transverse foramina, with a large branch from the stellate ganglion and a plexus of veins which form the vertebral vein low in the neck. It is anterior to the ventral rami of the cervical spinal nerves (C.2–C.6), ascending almost vertically to the transverse process of the axis, through which it turns laterally to the transverse foramen of the atlas; from here the *third part* issues medial to the rectus capitis lateralis, curving back and medially behind the lateral mass, the first cervical ventral spinal ramus being medial. It is then in a groove on the upper surface of the posterior arch of the atlas, entering the vertebral canal below the inferior border of the posterior atlanto-occipital membrane. This part,

Left brachio- cephalic vein
Internal thoracic artery
Scalenus anterior

Brachiocephalic trunk

Left common carotid artery

Left phrenic nerve

Left vagus nerve

Trachea

Left subclavian artery

Left recurrent laryngeal nerve

Oesophagus

Thoracic duct

Inferior cervical ganglion

Vertebral artery

Costocervical trunk

First thoracic ventral ramus
Superior intercostal artery
Deep cervical artery
Suprapleural membrane

10.91 Structures related to the left cervical pleura, as seen from below.

Transverse cervical nerve
Great auricular nerve
Sternocleido- mastoid
Phrenic nerve

Accessory nerve

Levator scapulae

Scalenus medius

Dorsal scapular nerve

Supraclavicular nerves

Dorsal scapular artery

Suprascapular nerve

Upper trunk

Middle trunk

Scalenus anterior

Sternothyroid and sternohyoid

Serratus anterior
Pectoralis minor
Thoraco-acromial artery
Lateral and posterior cord
Medial pectoral nerve
Subclavian artery (3rd part)
Suprascapular artery and vein
First rib
Superficial cervical artery
Intermediate tendon of omohyoid

10.92 The lower part of the posterior triangle showing the relations of the third part of the right subclavian artery. Note the clavicle has been removed but its outline is indicated by a dashed line; the middle trunk of the brachial plexus gives an unusual contribution to the medial cord.

10.93 Vertebral arteriogram (left): lateral view. 1. Vertebral artery, ascending part. 2. Loop between transverse foramina of axis and atlas. 3. Sub-occipital part. 4. Intracranial part. 5. Basilar artery. 6. Posterior cerebral branches. 7. Inferior cerebellar branches.

covered by the semispinalis capitis, is in the suboccipital triangle. The first cervical dorsal spinal ramus is between the artery and the posterior arch. The *fourth part* pierces the dura and arachnoid mater, ascends anterior to the hypoglossal roots (p. 1256) inclining anterior to the medulla oblongata where, at the lower pontine border, it unites with its fellow to form the midline basilar artery (10.88, 89).

Winckler (1972) has described variation in elastic and muscular tissue in the vertebral artery; in its first and third parts it appears adapted by increased elasticity to the greater mobility and lack of support in these regions.

Cervical branches of the vertebral artery

Spinal branches. These small branches enter the vertebral canal by the intervertebral foramina, supplying branches to the spinal cord and its membranes. They anastomose with other spinal arteries, which fork into ascending and descending rami, to unite with those above and below, forming two lateral anastomotic chains on the

posterior surfaces of the vertebral bodies near the attachment of their pedicles. From these chains branches supply the periosteum and vertebral bodies, while others communicate with similar branches across the midline; from these connections small rami join similar ones above and below, forming a median anastomotic chain on the posterior surfaces of the vertebral bodies.

Muscular branches. Arising from the vertebral artery as it curves round the lateral mass of the atlas, they supply the deep muscles of this region and anastomose with the occipital, ascending and deep cervical arteries.

Cranial branches of the vertebral artery

Meningeal branches. One or two of these branches from the vertebral artery near the foramen magnum ramify between the bone and dura mater in the cerebellar fossa, supplying bone, diploë and the falx cerebelli.

Posterior spinal artery. This may arise from the vertebral near
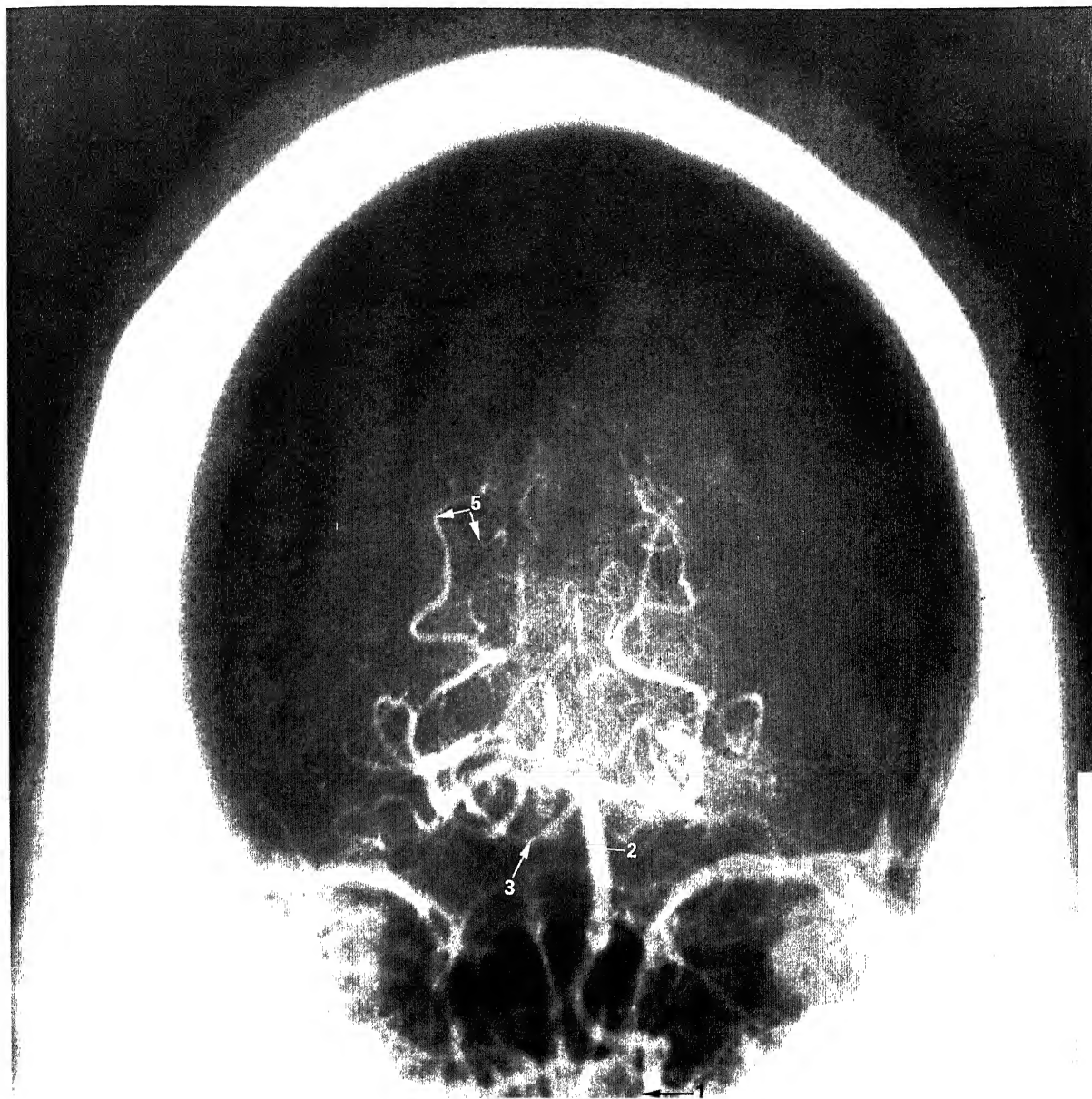
10.94 Vertebral arteriogram (left): anteroposterior view. 1. Left vertebral artery. 2. Basilar artery. 3. Right superior cerebellar artery. 4. Right posterior cerebral artery. 5. Branches of right posterior cerebral artery.

the medulla oblongata but most frequently from its posterior inferior cerebellar branch (see below). It passes posteriorly, descending as two branches, anterior and posterior, to the dorsal roots of the spinal nerves; these are reinforced by spinal twigs from the vertebral, ascending cervical, posterior intercostal and first lumbar arteries, which reach the vertebral canal by the intervertebral foramina, sustaining the posterior spinal arteries to the lower spinal levels (8.329).

Anterior spinal artery. A small branch arising near the vertebral's end, it descends anterior to the medulla oblongata and unites with its fellow at midmedullary level. The single trunk then descends on the ventral midline of the spinal cord, reinforced by a succession of small spinal rami entering the vertebral canal through the intervertebral foramina from the vertebral, ascending cervical, posterior intercostal and first lumbar arteries. They unite by ascending and descending branches as a single anterior median artery, which reaches

the lower spinal cord and filum terminale. This median artery is encased in the pia mater along the anterior median fissure; it supplies the spinal cord and inferiorly the cauda equina. Branches from the anterior spinal arteries and beginning of their common trunk pass into the medulla oblongata, with a central distribution sharply limited dorsally by the trigonum hypoglossi (p. 1218, 8.329).

Posterior inferior cerebellar artery (10.46). The largest branch, it is sometimes absent. Arising near the lower end of the olive, it curves back around it to ascend behind glossopharyngeal and vagal roots to the inferior border of the pons, where it curves and descends along the inferolateral border of the fourth ventricle. Finally it turns laterally into the cerebellar vallecula, dividing into medial and lateral branches. The *medial branch* runs back between the cerebellar hemisphere and inferior vermis, supplying both; the *lateral branch* supplies the inferior cerebellar surface as far as its lateral border, anastomosing with the anterior inferior and superior cerebellar

1533

arteries (from the basilar artery). Its trunk supplies the medulla oblongata and choroid plexus of the fourth ventricle, sending up a branch lateral to the (cerebellar) tonsil to supply the dentate nucleus. The medullary area supplied is dorsal to the olivary nucleus and lateral to the hypoglossal nucleus and its emerging fila.

Clinical anatomy. The posterior inferior cerebellar artery supplies the lateral medulla. Thrombosis therefore causes loss of function ('lateral medullary syndrome') in the nucleus ambiguus, nucleus of the tractus solitarius, vestibular and cochlear nuclei, spinocerebellar tracts, the lateral spinothalamic tract, trigeminal spinal nucleus and tract. The anterior spinal artery supplies the medial medulla; thrombosis of it ('medial medullary syndrome') affects the hypoglossal nucleus and nerve, medial lemniscus and corticospinal tract.

Medullary arteries. These are minute vessels from the vertebral and its branches, distributed to the medulla oblongata.

Basilar artery

This median vessel, formed by the junction of the vertebral arteries, extends from the lower to the upper pontine borders in the cisterna pontis (**10.86, 88**). It adjoins a shallow, median groove on the ventral pontine surface, between the abducent nerves at the lower pontine border and the oculomotor at the upper pontine border, where it divides into two posterior cerebral arteries.

Pontine branches. These are numerous and leave the front and sides of the basilar to supply the pons and adjacent parts.

Labyrinthine (internal auditory) artery. Long and slender, it may branch from the lower part of the basilar but more often from the anterior inferior cerebellar artery (see below); it accompanies facial and vestibulocochlear nerves into the internal acoustic meatus and is distributed to the internal ear (p. 1376). In a radiographic study of this artery Wende et al (1975) identified the origins of 238. Only 38 (16%) were from the basilar; 108 (45%) were from the anterior inferior cerebellar. The superior cerebellar artery accounted for 58 (25%), the posterior inferior cerebellar for 13 (5%). The remaining 21 (9%) were reduplicated and were branches of the basilar and one or other of the cerebellar arteries. They found a unilateral artery in 24 of 316 subjects. Others have recorded different incidences. Cavatori (1908) observed a basilar origin for the labyrinthine artery in about 70% in Italians; Stopford (1916) and Adachi and Hasche (1928) recorded it as most often from a trunk common to it and one of the cerebellar arteries. Gillilan (1972) has indicated racial variation.

Anterior inferior cerebellar artery (10.86). This branches from the lower part of the basilar and runs posterolaterally usually ventral to the abducent, facial and vestibulocochlear nerves, commonly forming a variable loop into the internal acoustic meatus below the nerves (Sunderland 1945a), from which the labyrinthine artery often arises. Emerging from the meatus the artery supplies the anterolateral region of the inferior cerebellar surface, anastomosing with the posterior inferior cerebellar branch of the vertebral. A few branches supply the inferolateral parts of the pons and sometimes the upper medulla oblongata.

Superior cerebellar artery (10.86). Arising near the basilar's end, it passes laterally below the oculomotor nerve which separates it from the posterior cerebral artery and curves round the cerebral peduncle below the trochlear nerve; arriving at the superior cerebellar surface, it divides into branches ramifying in the pia mater to supply this cerebellar aspect and anastomose with branches of inferior cerebellar arteries. It also supplies the pons, pineal body, superior medullary velum and tela choroidea of the third ventricle.

Posterior cerebral artery (10.86, 88, 89). Frequently double, this is larger than the superior cerebellar, from which it is separated near its origin by the oculomotor nerve and, lateral to the midbrain, by the trochlear nerve. Passing laterally, parallel with the superior cerebellar, it receives the posterior communicating artery, winds round the cerebral peduncle and reaches the tentorial cerebral surface, where it supplies the temporal and occipital lobes. Its branches are central and cortical.

Central branches. Several small *posteromedial central branches* (**10.88**) from the beginning of the posterior cerebral, with similar branches from the posterior communicating artery, pierce the posterior perforated substance to supply the anterior thalamus, lateral wall of the third ventricle and the globus pallidus. *Posterior choroidal branches* vary (Abbie 1933); one or more course over the lateral geniculate body and supply it before entering the posterior part of

the inferior cornu of the lateral ventricle via the lower part of the choroidal fissure. Others curl round the posterior end of the thalamus and traverse the transverse fissure, some going to the third ventricle's tela choroidea, some to traverse the upper choroidal fissure; they supply the choroid plexuses of the third and lateral ventricles and the fornix (Percheron 1977, p. 1220). Small posterolateral central branches arise from the posterior cerebral artery beyond the cerebral peduncle; they supply this and the posterior thalamus, colliculi, pineal gland and medial geniculate body.

Cortical branches. The temporal branches, usually two, are distributed to the uncus, parahippocampal, medial and lateral occipitotemporal gyri; occipital branches supply the cuneus, lingual gyrus and posterolateral surface of the occipital lobe; parieto-occipital branches supply the cuneus and precuneus. The posterior cerebral artery supplies the visual area (p. 1220) and other structures in the visual pathway.

2. Internal thoracic (mammary) artery

This arises inferiorly from the first part of the subclavian artery, about 2 cm above the sternal end of the clavicle, opposite the root of the thyrocervical trunk (**10.90, 91, 95**). It descends behind the first six costal cartilages about 1 cm from the lateral sternal border; level with the sixth intercostal space it divides into musculophrenic and superior epigastric branches.

Relations. At first it descends anteromedially behind the clavicle's sternal end, the internal jugular and brachiocephalic veins and the first costal cartilage. As it enters the thorax, the phrenic nerve crosses it obliquely from its lateral side, usually in front. The artery then descends almost vertically to its bifurcation; anterior to it are the pectoralis major, the first six costal cartilages and intervening external intercostal membranes and internal intercostals and terminations of the upper six intercostal nerves. It is separated from the pleura, down to the second or third cartilage, by a strong layer of fascia and below this by the transversus thoracis. It is accompanied by a chain of lymph nodes and venae comitantes uniting at about the third costal cartilage into a single vein medial to the artery. Its intermediate branches are as follows:

Pericardiacophrenic artery. A long, slender branch accompanying the phrenic nerve to the diaphragm, it descends between the pleura and pericardium, finally anastomosing with the musculophrenic and phrenic arteries.

Mediastinal arteries. These are distributed to the areolar tissue and lymph nodes in the anterior mediastinum and to the thymic vestiges.

Pericardial branches. These supply the upper anterior region of the pericardium.

Sternal branches. These are distributed to the transversus thoracis, the periosteum of the posterior sternal surface and the sternal red bone marrow.

The foregoing three groups, with small branches of the pericardiacophrenic, anastomose with branches of the posterior intercostal and bronchial arteries to form a *subpleural mediastinal plexus.*

Anterior intercostal branches. Distributed to the upper six intercostal spaces, two in each space, they pass laterally along the borders of the space to anastomose with the posterior intercostal arteries (and their collateral branches). They lie at first between the pleura and the internal intercostals, then between the intercostales intimi and the internal intercostals. They supply the intercostal muscles and send branches through them to the pectoral muscles, breast and skin.

Perforating branches. They traverse the upper five or six intercostal spaces with anterior cutaneous branches of the corresponding intercostal nerves. They enter the pectoralis major and, curving laterally, supply the muscle and skin. In the female the second to fourth branches supply the breast; during lactation they are enlarged.

Musculophrenic artery. This passes inferolaterally behind the seventh to ninth costal cartilages, traverses the diaphragm near the ninth and ends near the last intercostal space. It anastomoses with the inferior phrenic and the lower two posterior intercostal and ascending branches of the deep circumflex iliac arteries. Two anterior intercostal arteries branch from it for each of the seventh to ninth intercostal spaces, distributed like those in other spaces. The musculophrenic also supplies the lower part of the pericardium and the abdominal muscles.

Superior epigastric artery. It descends between the costal and xiphoid slips of the diaphragm, anterior to the lower fibres of the transversus thoracis and the upper fibres of the transversus abdominis. Entering the rectus sheath, at first behind the muscle and then perforating and supplying it, it anastomoses with the inferior epigastric branch of the external iliac. Branches perforate the sheath to supply the abdominal skin; a branch anterior to the xiphoid process anastomoses with its fellow. The artery supplies the diaphragm; on the right small branches reach the falciform ligament to anastomose with the hepatic artery.

3. Thyrocervical trunk

This short, wide artery, from the front of the subclavian's first part near the medial border of the scalenus anterior, divides almost at once into the inferior thyroid, suprascapular and superficial cervical arteries (10.73, 154).

Inferior thyroid artery. This is looped; first it **ascends** anterior to the medial border of the scalenus anterior, turns **medially** just below the sixth cervical transverse process, passing anterior to the vertebral vessels and posterior to the carotid sheath and its contents and usually the sympathetic trunk, whose middle cervical ganglion usually adjoins the vessel. It finally **descends** on the longus colli to the lower border of the thyroid gland. As it approaches this, its relation to the recurrent laryngeal nerve is surgically important (p. 1252). Nearing the gland the artery usually passes behind the nerve, but nearer the gland, on the right, the nerve is with equal frequency anterior or posterior to or amongst the branches of the artery; the left nerve is usually posterior. Relations between the terminal branches of artery and nerve are very variable (Bowden 1955). On the left, near its origin, the artery is crossed anteriorly by the thoracic duct, curving inferolaterally to its end.

Muscular branches. These supply the infrahyoid muscles, longus colli, scalenus anterior and the inferior pharyngeal constrictor.

Ascending cervical artery. A small branch, it arises as the inferior thyroid turns medially behind the carotid sheath and ascends on the anterior tubercles of the cervical transverse processes between the scalenus anterior and the longus capitis. It supplies the adjacent muscles and has one or two spinal branches which enter the vertebral canal through the intervertebral foramina to supply the spinal cord and membranes and vertebral bodies, as do the spinal branches of the vertebral artery. The ascending cervical artery anastomoses with the vertebral, ascending pharyngeal, occipital and deep cervical arteries.

Inferior laryngeal artery. It ascends on the trachea with the recurrent laryngeal nerve, enters the larynx at the inferior constrictor's lower border and supplies the laryngeal muscles and mucosa, anastomosing also with its contralateral fellow, and with the superior laryngeal branch of the superior thyroid artery.

Pharyngeal branches. These supply the lower pharynx: *tracheal branches* the trachea (anastomosing with the bronchial arteries), and *oesophageal branches* the oesophagus (anastomosing with the oesophageal branches of thoracic aorta). Inferior and ascending *glandular branches* supply the posterior and inferior regions of the thyroid gland, anastomosing with the opposite inferior and ipsilateral superior thyroid arteries. The ascending branch also supplies the parathyroid glands.

Suprascapular artery (10.92). This first descends laterally across the scalenus anterior and phrenic nerve, posterior to the internal jugular vein and sternocleidomastoid; it then crosses anterior to the subclavian artery and brachial plexus, posterior and parallel to the clavicle and subclavius and the inferior belly of the omohyoid, to reach the superior scapular border. Here it passes above (sometimes under) the superior transverse ligament, separating it from the suprascapular nerve, to enter the supraspinous fossa (10.96), where it lies on the bone, supplying the supraspinatus. It descends behind the scapular neck, through the great scapular notch deep to the inferior transverse ligament to the deep surface of the infraspinatus, where it anastomoses with the circumflex scapular and deep branch of the transverse cervical artery. Besides supplying the sternocleidomastoid, subclavius and infraspinatus, it has a *suprasternal branch* which crosses the sternal end of the clavicle to the skin of the upper thorax and an *acromial branch* which pierces the trapezius to supply the skin over the shoulder, anastomosing with the thoracoacromial and posterior circumflex humeral arteries. As the supra-
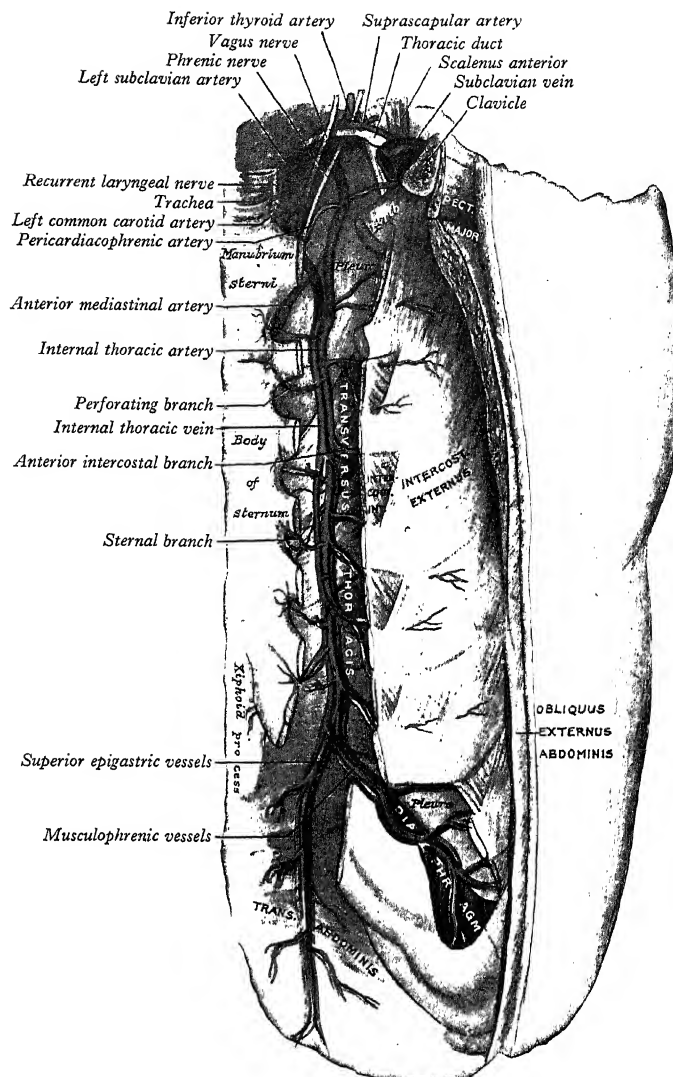
10.95 The left internal thoracic artery and vein and their main branches. The lateral end of the resected clavicle has been artificially elevated.

scapular artery passes the superior transverse ligament, a branch of it enters the subscapular fossa beneath the subscapularis; this anastomoses with the subscapular artery and the deep branch of the transverse cervical. It also supplies the acromioclavicular and glenohumeral joints, the clavicle and scapula. It may arise from the third part of the subclavian artery.

Superficial cervical artery (10.92). At a higher level than the suprascapular, it crosses anterior to the phrenic nerve, the scalenus anterior and brachial plexus and is covered by the internal jugular vein, sternocleidomastoid and platysma. It crosses the posterior triangle's floor to the anterior margin of the levator scapulae, ascending deep to the anterior part of the trapezius, supplying it, the adjoining muscles and the cervical lymph nodes. It anastomoses with the superficial ramus of the descending branch of the occipital artery. (See also p. 1536: variations of superficial cervical and dorsal scapular arteries.)

4. Costocervical trunk

On the right, this short vessel arises posteriorly from the second part of the subclavian artery, and, on the left, from its first part (10.91, 92). It arches back above the cervical pleura to the first rib's neck, dividing here into superior intercostal and deep cervical branches.

Superior intercostal artery. It descends between the pleura and necks of the first and second ribs to anastomose with the third

posterior intercostal artery (10.91). Crossing the neck of the first rib it is medial to the ventral branch of the first thoracic spinal nerve, which it crosses at a lower level, and lateral to the stellate ganglion. In the first space it provides the first posterior intercostal artery, similar in distribution to the lower posterior intercostals. It descends to become the second posterior intercostal artery, usually joining a branch from the third; it is not constant, and is more common on the right; when absent, it is replaced by a direct aortic branch.

Deep cervical artery (10.84). Usually arising from the costo-cervical trunk, it is analogous in its first segment to a posterior branch of a posterior intercostal artery: occasionally it is a separate branch of the subclavian. Passing back above the eighth cervical spinal nerve between the seventh cervical transverse process and the neck of the first rib (sometimes between the sixth and seventh cervical transverse processes), it then ascends between the semispinales capitis and cervicis to the second cervical level. It supplies adjacent muscles and anastomoses with the deep branch of the descending branch of the occipital artery (p. 1519) and branches of the vertebral. A spinal branch enters the vertebral canal between the seventh cervical and first thoracic vertebrae.

5. Dorsal scapular artery

This arises from the third or less often second part of the subclavian, passing laterally through the brachial plexus in front of the scalenus medius and then deep to the levator scapulae to the superior scapular angle; here it descends with the dorsal scapular nerve under the rhomboids along the medial scapular border to the inferior angle (10.92, 96). It supplies the rhomboids, latissimus dorsi and trapezius and anastomoses with the suprascapular, subscapular and posterior branches of some posterior intercostal arteries. It has a small branch, sometimes arising directly from the subclavian, for the scalenus anterior.

Variations. About a third of the superficial cervical and dorsal

scapular arteries arise in common from the thyrocervical trunk as a *transverse cervical artery*, with a superficial (*superficial cervical artery*) and a deep branch (*dorsal scapular artery*); the latter passes laterally anterior to the brachial plexus and then posterior to the levator scapulae.
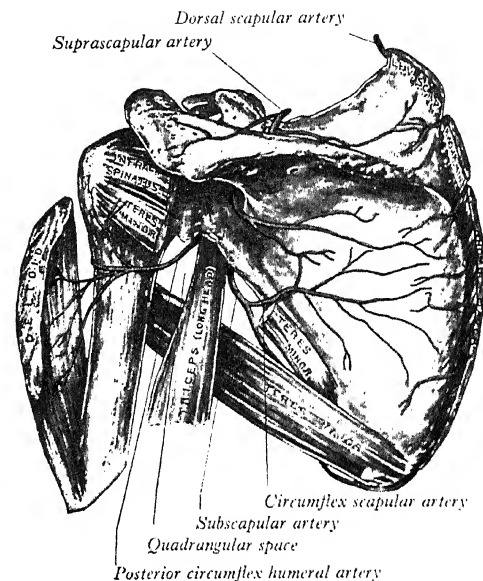
10.96 Scapular anastomoses of the left side: dorsal aspect.

The axilla is a pyramidal region between the upper thoracic wall and the arm. Its blunt **apex** continues into the root of the neck (*cervico-axillary canal*) between the external border of the first rib, superior scapular border, posterior surface of the clavicle and the medial aspect of the coracoid process; through it pass the axillary vessels and nerves. Its imaginary **base**, facing down, is broad at the chest, narrow at the arm and corresponds to the skin and a thick layer of *axillary fascia*, between the inferior borders of the pectoralis major in front and the latissimus dorsi behind. It is of course convex up, conforming to the armpit's concavity. The *anterior wall* is formed by the pectorales major et minor, the former covering the whole wall, the latter its intermediate part. The interval between the upper border of the pectoralis minor and clavicle is occupied by the clavipectoral fascia. The *posterior wall* is formed by the subscapularis above, teres major and latissimus dorsi below. **Medial** are the first four ribs with their intercostal muscles and the upper part of serratus anterior; this 'wall' is convex laterally. **Laterally** anterior and posterior walls converge, the 'wall' being narrow, consisting of the humeral intertubercular sulcus; the lateral angle lodges the coracobrachialis and biceps.

The axilla contains axillary vessels, the infraclavicular part of the brachial plexus and its branches, lateral branches of some intercostal nerves, many lymph nodes and vessels, loose adipose areolar tissue and in many instances the 'axillary tail' of the breast. The axillary vessels and brachial plexus run from the apex to the base along the lateral wall and nearer to the anterior wall, the axillary vein being anteromedial to the artery. Owing to the obliquity of the upper ribs, the neurovascular bundle, emerging from behind the clavicle, crosses the first intercostal space; its relations are therefore different at upper and lower levels. Thoracic branches of the axillary artery are in contact with the pectoral muscles; along the lateral margin of the pectoralis minor the lateral thoracic artery reaches the thoracic wall. Subscapular vessels descend on the posterior wall at the lower margin of the subscapularis, and subscapular and thoracodorsal nerves cross the anterior surface of the latissimus dorsi at different inclinations; circumflex scapular vessels wind round the lateral scapular border; posterior circumflex humeral vessels and the axillary nerve curve back and laterally around the humeral surgical neck. No large vessel lies on the medial 'wall', which is crossed proximally only by small branches of the superior thoracic artery. The long thoracic nerve descends on the serratus anterior and the intercostobrachial nerve perforates the upper anterior part of this wall,

crossing the axilla to its lateral 'wall'. The position and arrangement of lymph nodes are described on page 1613, nerves on page 1266 et seq.

Clinical Anatomy. When axillary suppuration occurs, fascial arrangement affects the spread of pus. As described on page 839, the clavipectoral fascia, between the clavicle and superomedial border of the pectoralis minor, splits to enclose the muscle, blending at its lateral border with the axillary fascia in the anterior axillary fold. Suppuration may be superficial or deep to this layer, either between the pectoral muscles or behind the pectoralis minor; in the former an abscess would appear at the edge of the anterior axillary fold or the groove between the deltoid and pectoralis major; in the latter, pus would tend to surround vessels and nerves and ascend into the neck, the direction of least resistance; pus may also track along vessels into the arm. When an axillary abscess is incised, a knife should enter the axillary 'base', midway between the anterior and posterior margins and near the thoracic side to avoid the lateral thoracic, subscapular and axillary vessels on the anterior, posterior and lateral walls. Relations of vessels and nerves in the axilla are important when lymph nodes are removed from the axilla in operations for mammary carcinoma; the positions of major structures in the lateral wall must be remembered.

The axillary artery (10.97), a continuation of the subclavian, begins at the first rib's outer border, ending nominally at the interior border of the teres major where it becomes brachial. Its direction varies with the limb's position: thus it is almost straight when the arm is raised at right angles, concave up when the arm is elevated above this and convex up and laterally with the arm pendent. At first deep, it becomes superficial, covered only by the skin and fasciae. The pectoralis minor crosses it and divides it into **three parts**: proximal, posterior and distal to the muscle.

Relations of the first part. **Anterior** are the skin, superficial fascia, platysma, supraclavicular nerves, deep fascia, clavicular fibres of the pectoralis major and the clavipectoral fascia. This part is crossed anteriorly by the lateral pectoral nerve, the loop of communication between it and the medial pectoral nerve, and by the thoraco-acromial and cephalic veins. **Posterior** are the first intercostal space and external intercostal, the first and second digitations of the serratus anterior, the long thoracic and medial pectoral nerves and the medial cord of the brachial plexus. **Lateral** is the posterior cord of the brachial plexus. **Anteromedial** is the axillary vein. The first part is enclosed with the axillary vein and brachial plexus in a fibrous *axillary sheath*, continuous with the prevertebral layer of the deep cervical fascia.

Relations of the second part. **Anterior** are the skin, superficial and deep fascia, pectoralis major and minor. Posterior are the posterior cord of the brachial plexus and the areolar tissue between it and the subscapularis. **Medial** is the axillary vein, separated from it by the medial cord of the brachial plexus and medial pectoral nerve. **Lateral** is the lateral cord of the brachial plexus, separating it from the coracobrachialis. The cords of the brachial plexus thus surround the second part on three sides, with the dispositions implied by their names, and separate it from the vein and adjacent muscles.

Relations of the third part. **Anterior** are pectoralis major, distal to this skin and fasciae. **Posterior** are the lower part of the subscapularis and tendons of the latissimus dorsi and teres major. **Lateral** is the coracobrachialis. **Medial** is the axillary vein. Branches of the brachial plexus are arranged as follows: **laterally** the lateral root and then trunk of the median nerve and, for a short distance, the musculocutaneous nerve; **medially** the medial cutaneous nerve of the forearm between the axillary artery and vein anteriorly, between them posteriorly the ulnar nerve; the medial cutaneous nerve of upper arm is medial to the vein; anterior is the medial root of the median nerve and posterior are radial and axillary nerves, the latter only to the distal border of the subscapularis.

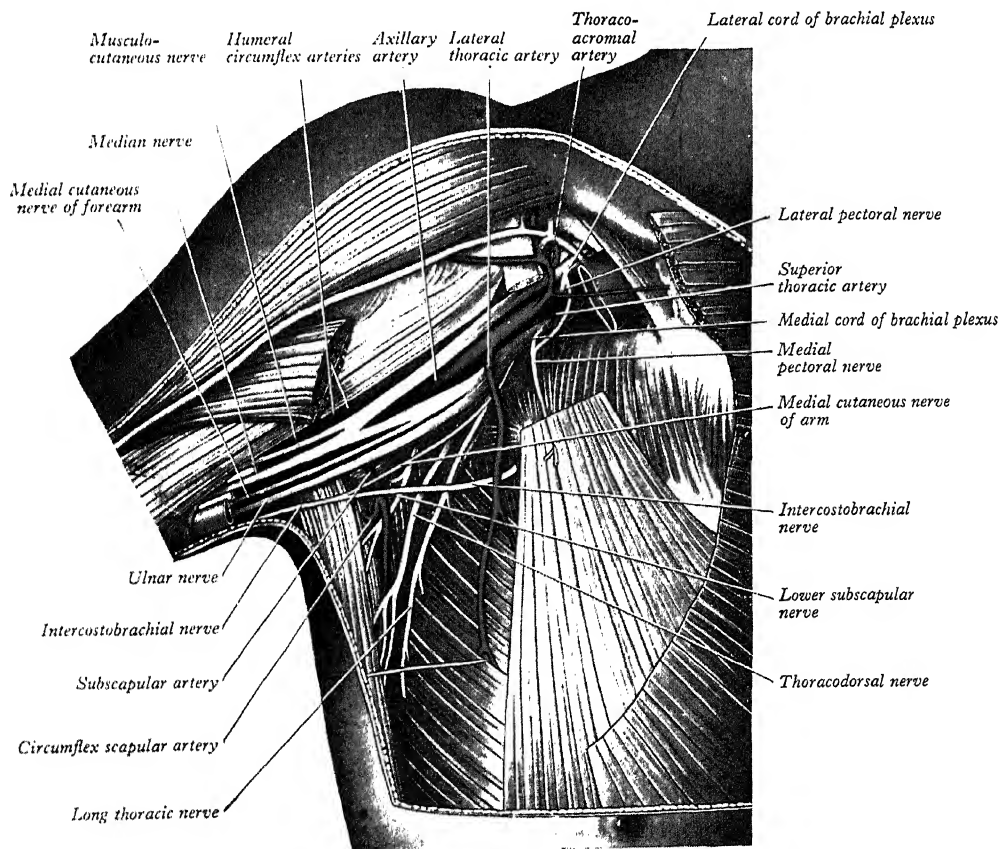## BRANCHES OF THE AXILLARY ARTERY

The artery's branches are superior thoracic, thoraco-acromial, lateral thoracic, subscapular, anterior and posterior circumflex humeral.

Superior thoracic artery (10.97). A small vessel from the first part of the axillary near the lower border of the subclavius (sometimes from the thoraco-acromial), it runs anteromedially above the medial border of the pectoralis minor, then passes between it and the pectoralis major to the thoracic wall. It supplies these muscles and the thoracic wall, anastomosing with the internal thoracic and upper intercostal arteries.

Thoraco-acromial (acromio-thoracic) artery (10.92, 97). A short branch from the second part, it is at first overlapped by the pectoralis minor; skirting its medial border, it pierces the clavipectoral fascia and divides into the pectoral, acromial, clavicular and deltoid branches.

Pectoral branch. This descends between the pectoral muscles, is distributed to them and the breast and anastomoses with the intercostal branches of the internal thoracic and lateral thoracic arteries.

Acromial branch. It crosses the coracoid process under the deltoid,

Musculo-cutaneous nerve · Humeral circumflex arteries · Axillary artery · Lateral thoracic artery · Thoraco-acromial artery · Lateral cord of brachial plexus

Median nerve

Medial cutaneous nerve of forearm

Ulnar nerve

Intercostobrachial nerve

Subscapular artery

Circumflex scapular artery

Long thoracic nerve

Lateral pectoral nerve

Superior thoracic artery

Medial cord of brachial plexus

Medial pectoral nerve

Medial cutaneous nerve of arm

Intercostobrachial nerve

Lower subscapular nerve

Thoracodorsal nerve

10.97 The right axillary and its branches. The pectoralis major and part of the pectoralis minor have been removed. Prominent but unlabelled features are the medial and lateral roots of the median nerve.

which it supplies, pierces the muscle and ends on the acromion, anastomosing with rami of the suprascapular, deltoid branch of the thoraco-acromial and posterior circumflex humeral arteries.

Clavicular branch. Ascending medially between the clavicular part of the pectoralis major and clavipectoral fascia, it supplies the sternoclavicular joint and subclavius.

Deltoid branch. It often arises with the acromial, crossing the pectoralis minor to accompany the cephalic vein between the pectoralis major and deltoid, supplying both.

Lateral thoracic artery (10.97). Following the lateral border of the pectoralis minor to the thoracic wall, it supplies the serratus anterior and pectoral muscles, the axillary lymph nodes and subscapularis; it anastomoses with the internal thoracic, subscapular, and intercostal arteries and the pectoral branch of the thoraco-acromial artery. In females it is large and has lateral mammary branches which curve round the lateral border of the pectoralis major to the mammary gland.

Subscapular artery (10.96, 97). The largest branch of the axillary, it usually arises at the distal (inferior) border of the subscapularis which it follows to the inferior scapular angle, where it anastomoses with the lateral thoracic and intercostal arteries and the deep branch of the transverse cervical. It supplies adjacent muscles and the thoracic wall. It is accompanied distally by the nerve to the latissimus dorsi; about 4 cm from its origin it divides into the circumflex scapular artery and the thoracodorsal artery. The *circumflex scapular artery*, the larger of the two, curves backwards around the lateral scapular border, traversing a *triangular space* between subscapularis above and teres major below and the long head of the triceps laterally. It enters the infraspinous fossa under the teres minor and then divides. One branch (*infrascapular*) enters the subscapular fossa deep to the subscapularis, anastomosing with the suprascapular and dorsal scapular arteries (or deep branch of the transverse cervical); the other continues along the lateral scapular border between the teres major and minor and, dorsal to the inferior angle, anastomoses with the deep branch of the transverse cervical artery. Small branches supply the posterior part of the deltoid and the long head of the triceps, anastomosing with an ascending branch of the arteria profunda brachii. The other terminal branch of the subscapular artery, the *thoracodorsal artery*, follows the lateral margin of the scapula, posterior to the lateral thoracic, between the latissimus dorsi and serratus anterior. It supplies these two muscles and teres major and intercostales, anastomosing with intercostal arteries.

Anterior circumflex humeral artery (10.97). Arising from the lateral side of the axillary artery at the distal border of the subscapularis, runs horizontally behind coracobrachialis and short head of biceps, anterior to the surgical neck of the humerus. Reaching the intertubercular sulcus, it sends an ascending branch to supply the humeral head and shoulder joint. It continues laterally under the long head of biceps and deltoid, anastomosing with the posterior circumflex humeral artery.

Posterior circumflex humeral artery (10.96). Larger than the anterior, it branches from the third part of the axillary at the distal border of the subscapularis and runs back with the axillary nerve through a *quadrangular space*, bounded by the subscapularis, the capsule of the shoulder joint and the teres minor above, the teres major below, the long head of triceps medially and the surgical neck of the humerus laterally. It curves round the humeral neck and supplies the shoulder joint, deltoid, teres major and minor, and long and lateral heads of triceps, giving off a descending branch to anastomose with the deltoid branch of the arteria profunda brachii and with the anterior circumflex humeral and acromial branches of the suprascapular and thoraco-acromial arteries.

Surface anatomy. Pulsation of the axillary artery can be felt against the axillary lateral wall. Its upper segment can be mapped out, when the arm is raised, by a line from this to the midpoint of the clavicle.

Variations. Branches vary considerably; an alar thoracic, often from the second part, may supply fat and lymph nodes in the axilla. Occasionally the subscapular, circumflex humeral and arteria profunda arise in common and then branches of the brachial plexus surround this instead of the axillary artery. The posterior circumflex humeral artery may be from the arteria profunda brachii, passing back below the teres major instead of traversing the quadrangular
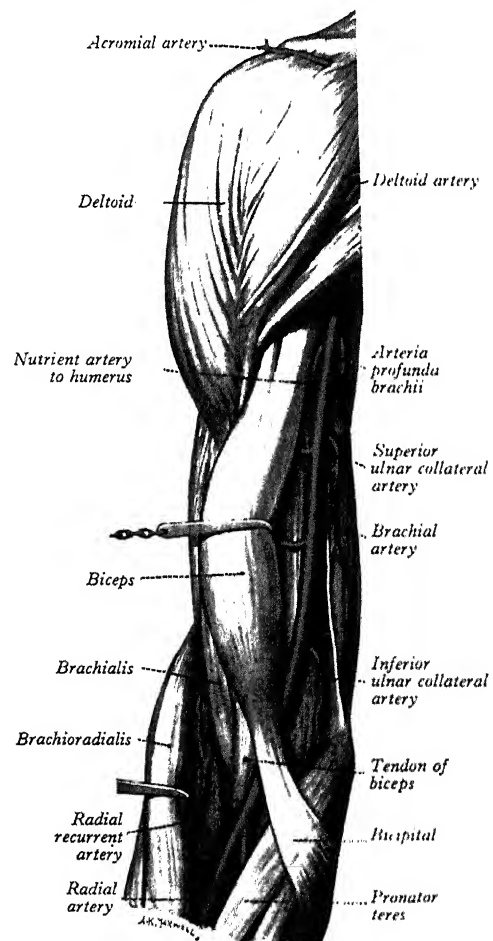
space. Sometimes (anomalous 'high division') the axillary divides into radial and ulnar arteries and is occasionally the source of the anterior interosseous artery.

Clinical anatomy. Axillary compression is most effective against the humerus. Except for the popliteal, the axillary artery is more frequently lacerated by violence than any other, being most susceptible when diseased. It has been ruptured in attempts to reduce old dislocations, especially when the artery is adherent to the articular capsule.

˟ERY

The brachial artery (10.98, 102), a continuation of the axillary, begins at the distal (inferior) border of the tendon of teres major and ends about a centimetre distal to the elbow joint (at the level of the neck of the radius) by dividing into radial and ulnar arteries. At first it is medial to the humerus, but gradually spirals anterior to it until it lies midway between the humeral epicondyles. Its pulsation can be felt throughout.

Relations. The artery is wholly superficial, covered **anteriorly** only by skin and superficial and deep fasciae; the bicipital aponeurosis crosses it anteriorly at the elbow, separating it from the median cubital vein; the median nerve crosses it **lateromedially** near the distal attachment of coracobrachialis. **Posterior** are the long head of triceps, separated by the radial nerve and arteria profunda brachii and then successively by: the medial head of triceps, the attachment of coracobrachialis and the brachialis. **Lateral** are: proximally the median nerve and coracobrachialis and distally the biceps and the muscles overlapping the artery. **Medial** are: proximally the medial cutaneous nerve of forearm and ulnar nerve, distally the median nerve and basilic vein (separated distally by the deep fascia). With

Acromial artery
Deltoid artery
Deltoid
Nutrient artery to humerus
Arteria profunda brachii
Superior ulnar collateral artery
Brachial artery
Biceps
Inferior ulnar collateral artery
Brachialis
Brachioradialis
Tendon of biceps
Radial recurrent artery
Bicipital
Radial artery
Pronator teres

10.98 The right brachial artery and its branches.

the artery are two venae comitantes, connected by transverse and oblique branches.

At the elbow the brachial artery sinks deeply into the triangular intermuscular cubital fossa. The fossa's base is an inter-epicondylar line, the sides being the medial edge of the brachioradialis and the lateral margin of pronator teres; the 'floor' consists of brachialis and supinator. The fossa contains the tendon of the biceps, the terminal part of the brachial artery and accompanying veins, the commencement of the radial and ulnar arteries and parts of the median and radial nerves. The brachial artery is central and it divides near the neck of the radius into its terminal branches, the radial and ulnar arteries. **Anterior** to it are the skin, superficial fascia and median cubital vein, separated by the bicipital aponeurosis. **Posteriorly** the brachialis separates it from the elbow joint. The median nerve is **medial** proximally but is separated from the ulnar artery by the ulnar head of the pronator teres. **Lateral** are the tendon of biceps and the radial nerve, the latter concealed between supinator and brachioradialis.

Variations. The brachial artery, with the median nerve, may diverge from the medial border of the biceps, descending towards the medial humeral epicondyle, usually behind a *supracondylar process* from which a fibrous arch crosses the artery, and which then runs behind or through the pronator teres to the elbow. This resembles the normal arrangement in some carnivores (p. 626). Occasionally the artery divides proximally into two trunks which reunite. Frequently it divides more proximally than usual into radial, ulnar and common interosseous arteries. Most often the radial branches arise proximally, leaving a common trunk for the ulnar and common interosseous; sometimes the ulnar arises proximally, the radial and common interosseous forming the other division; the common interosseous may also arise proximally. Sometimes slender *vasa aberrantia* connect the brachial to the axillary artery or to one of the forearm arteries, usually the radial. The brachial artery may be crossed by muscular or tendinous slips from the coracobrachialis, biceps, brachialis or pronator teres.

Branches. These are arteria profunda brachii, nutrient, superior and inferior ulnar collateral, muscular, radial and ulnar arteries.

Arteria profunda brachii (10.98, 99, 102). A large branch from the posteromedial aspect of the brachial, distal to the teres major, follows the radial nerve closely, at first back between the long and medial heads of the triceps, then in the nerve's groove covered by the lateral head of triceps; here it divides into terminal branches (10.102). Apart from the muscular branches, it supplies the following: the nutrient, deltoid, middle collateral and radial collateral arteries.

Nutrient artery. This enters the humerus posterior to the deltoid tuberosity but may be absent.

Deltoid (ascending) branch. Ascending between the lateral and long heads of triceps, it anastomoses with a descending branch of the posterior humeral circumflex artery.

Middle collateral (posterior descending) branch. The larger terminal vessel, it arises behind the humerus and descends in the medial head of the triceps to the elbow (10.100), anastomosing with the interosseous recurrent artery behind the lateral epicondyle; it often has a small branch which accompanies the nerve to the anconeus.

Radial collateral. The other terminal branch, this is the artery's continuation (10.101). It accompanies the radial nerve through the lateral intermuscular septum, descending between the brachialis and brachioradialis anterior to the lateral epicondyle, anastomosing with the radial recurrent artery.

Nutrient artery of the humerus. This arises near the mid-level of the upper arm, and enters the nutrient canal near the attachment of coracobrachialis; it is directed distally.

Superior ulnar collateral artery (10.98, 100, 102). It arises a little distal to the upper arm's mid-level, often as a branch from the arteria profunda brachii. It accompanies the ulnar nerve, piercing the medial intermuscular septum to descend between the medial epicondyle and olecranon, ending deep to flexor carpi ulnaris by anastomosing with the posterior ulnar recurrent and inferior collateral arteries; sometimes a branch of it passing anterior to the medial epicondyle anastomoses with the anterior ulnar recurrent artery.

Inferior ulnar collateral (supratrochlear) artery (10.98, 102, 103). It begins about 5 cm proximal to the elbow, passes medially between the median nerve and brachialis and, piercing the medial inter-
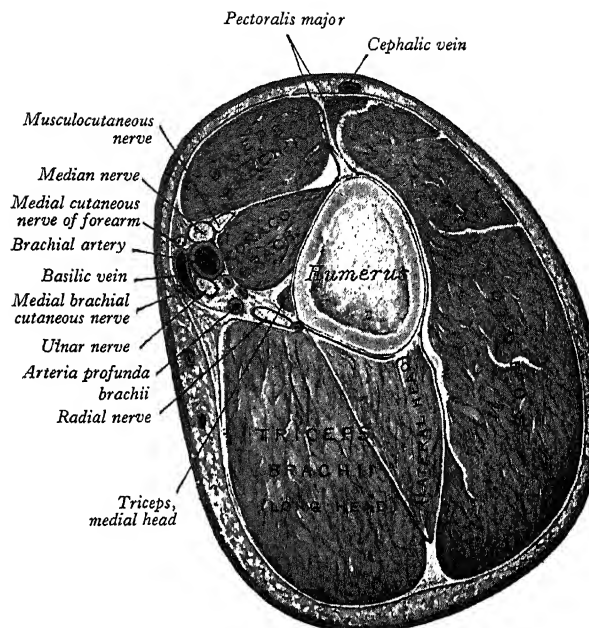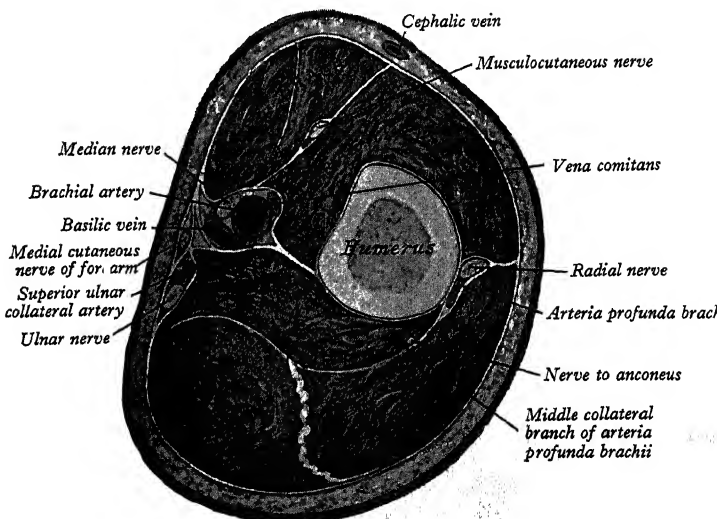

10.99 Transverse section through the right arm at the junction of the proximal and middle thirds of the humerus: proximal aspect.

muscular septum, curls round the humerus between the triceps and bone, forming, by its junction with the middle collateral branch of arteria profunda brachii, an arch proximal to the olecranon fossa. As it lies on brachialis it has branches descending anterior to the medial epicondyle to anastomose with the anterior ulnar recurrent artery. Behind the epicondyle a branch anastomoses with the superior ulnar collateral and posterior ulnar recurrent arteries.

Muscular arteries from the brachial. These are distributed to the coracobrachialis, biceps and brachialis.

Clinical anatomy

Compression of the brachial artery may be effected at almost any level; if proximal, it should be directed laterally, if distal, backwards. The most favourable site is about midway, where the artery is on the tendon of the coracobrachialis and still medial to the humerus; pressure should be exerted slightly posterolaterally.

10.100 Transverse section through the right arm, a little below the middle of the shaft of the humerus: proximal aspect.
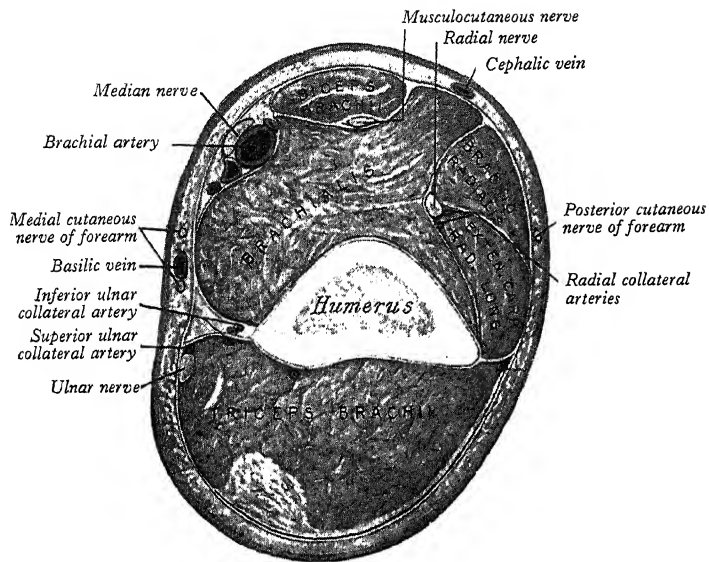
10.101 Transverse section through the right arm, 2 cm above the medial epicondyle of the humerus: proximal aspect.
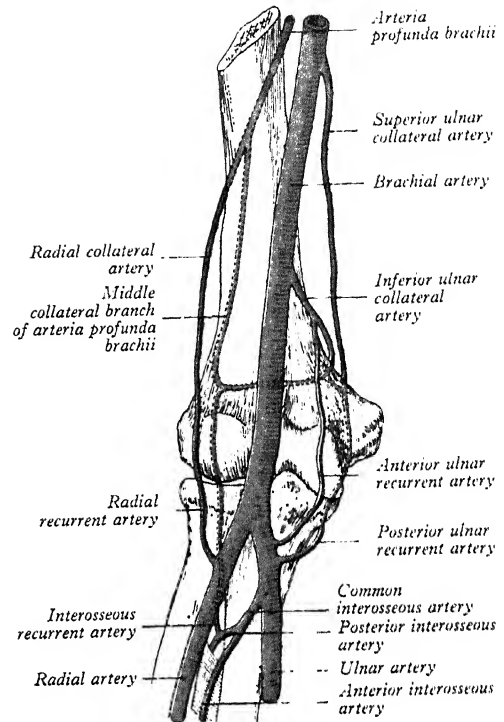

10.102 The arterial anastomoses around the (right) elbow joint. Anterior side seen from the front.
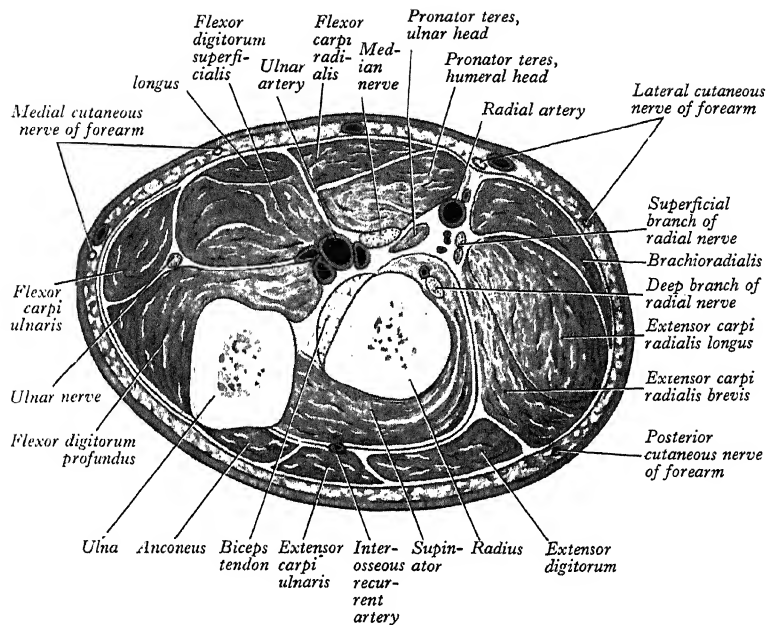
RADIAL ARTERY

The radial artery (**10.103–105**), though smaller than the ulnar, appears a more direct continuation of the brachial. It begins about 1 cm distal to the bend of the elbow (level of the neck of the radius, **10.102**), then descends along the lateral side of the forearm to the wrist, where it is palpable between the flexor carpi radialis medially and the salient anterior border of the radius. It then curls postero-laterally round the carpus, beneath the tendons of abductor pollicis longus and extensor pollicis brevis and longus, to the proximal end of the first intermetacarpal space, swerving medially between the heads of the first dorsal interosseous into the palm and then crossing medially to form the deep palmar arch with the deep branch of the ulnar artery. The radial artery is thus divisible into parts: in the forearm, wrist and hand.

In the forearm (**10.103–106**) the artery extends from the medial side of the neck of the radius to the front of its styloid process, being medial to the radial shaft proximally, but anterior to it distally. Proximally it is overlapped anteriorly by the belly of brachioradialis, whereas the rest is covered only by the skin, superficial and deep fasciae. Posterior are successively: the tendon of biceps, supinator, the distal attachment of pronator teres, radial head of flexor digitorum superficialis, flexor pollicis longus, pronator quadratus and the lower end of the radius (where its pulsation is most accessible). Proximally pronator teres is medial, brachioradialis lateral; distally the tendon of flexor carpi radialis is medial, that of brachioradialis lateral. The superficial branch of the radial nerve is lateral in the vessel's middle third, and filaments of the lateral cutaneous nerve of the forearm run along its distal part as it curves round the carpus. The vessel is accompanied by paired venae comitantes.

At the wrist (**10.107, 108**) the radial artery passes on to the dorsal aspect of the carpus between the lateral carpal ligament and tendons of abductor pollicis longus and extensor pollicis brevis. It crosses the scaphoid bone and trapezium (in the 'anatomical snuff-box'), where again its pulsation is obvious, and as it passes between heads of the first dorsal interosseous it is crossed by the tendon of extensor pollicis longus. Between the thumb extensors it is crossed by the beginning of the cephalic vein and the digital branches of the radial nerve supplying the thumb and index.
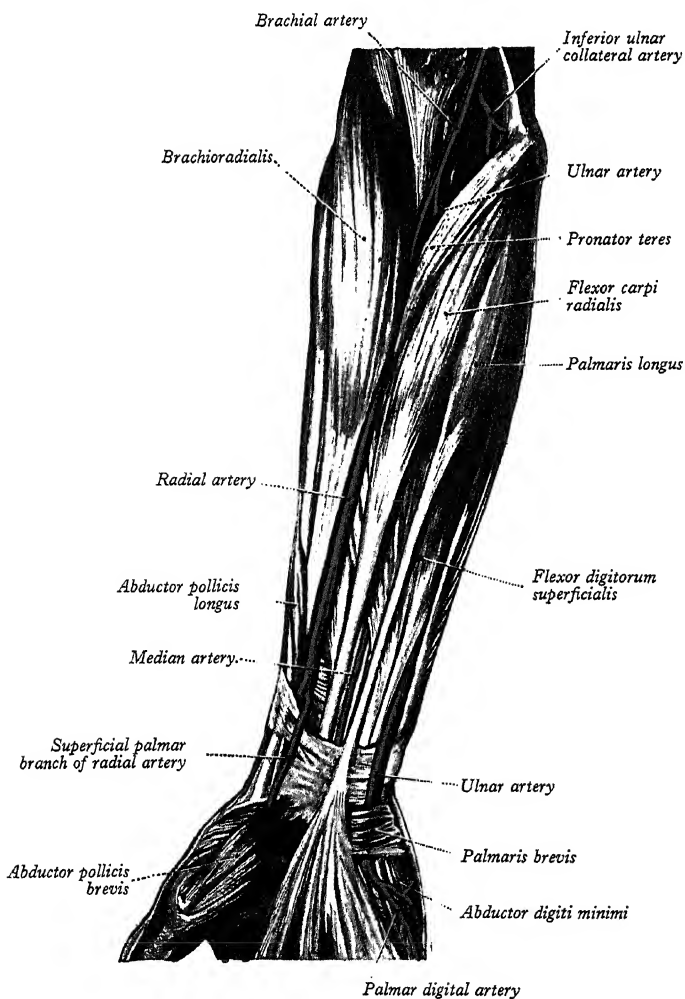
10.103 The right radial and ulnar arteries, superficial dissection.

10.104 Transverse section through the right forearm at the level of the radial tuberosity: distal aspect.

In the hand (10.109) the radial artery, having traversed the first interosseous space between the heads of the first dorsal interosseous, crosses the palm, at first deep to the oblique head of adductor pollicis and then between its oblique and transverse heads or through the transverse head. At the fifth metacarpal base it anastomoses with the deep branch of the ulnar artery, completing the *deep palmar arch* (10.105).

Variations. Sometimes the radial artery arises proximally, usually from the axillary or beginning of the brachial artery. In the forearm it is sometimes superficial to the deep fascia and occasionally superficial to the thumb extensor tendons (see also under 'Variations of the Brachial Artery', above).

Radial recurrent artery (10.102, 105). This arises just distal to the elbow, passing between superficial and deep branches of the radial nerve to ascend behind the brachioradialis, anterior to the supinator and brachialis; it supplies these muscles and the elbow joint, anastomosing with the radial collateral branch of the arteria profunda brachii.

Muscular branches. These are distributed to muscles on the radial side of the forearm.

Palmar carpal branch (10.105). A small vessel, it arises near the distal border of pronator quadratus and crosses the anterior surface of the distal end of the radius, near the palmar carpal surface, passing medially to anastomose behind the long flexor tendons with the palmar carpal branch of the ulnar; this transverse anastomosis is joined by longitudinal branches from the anterior interosseous and recurrent branches from the deep palmar arch, forming a *cruciate palmar carpal arch*, which, by descending branches, supplies the carpal articulations and bones. (Although so named this is usually sited near the wrist joint on the distal forearm bones.)

Superficial palmar branch (10.109). Arising from the radial artery just before it curves round the carpus, it passes through and occasionally over the thenar muscles, which it supplies, sometimes anastomosing with the end of the ulnar artery to complete a superficial palmar arch.

Dorsal carpal branch. This arises deep to the pollicial extensor tendons, runs medially across the dorsal carpal surface under them and anastomoses with the ulnar dorsal carpal branch and also with the anterior and posterior interosseous arteries to form a *dorsal carpal arch*. The carpal arches are both close to bone and supply the distal epiphyseal parts of the radius and ulna. From the dorsal arch three *dorsal metacarpal arteries* descend on the second to fourth dorsal interosseous muscles and bifurcate into the *dorsal digital*

branches for the adjacent sides of all four fingers; they anastomose with the palmar digital branches from the superficial palmar arch; near their origins they also anastomose with the deep palmar arch by the *proximal perforating arteries* and, near their bifurcation, with the palmar digital rami of the superficial palmar arch by *distal perforating arteries*.

First dorsal metacarpal artery (10.108). A branch of the radial just before it passes between the heads of the first dorsal interosseous, it divides almost at once into two branches supplying the adjacent sides of the pollex and index; the radial side of the pollex receives a branch direct from the radial artery itself (see below).

Arteria princeps pollicis (10.105). This arises from the radial as it turns into the palm, and descends on the palmar aspect of the first metacarpal under the oblique head of adductor pollicis lateral to the first palmar interosseous. At the base of the proximal phalanx, deep to the tendon of flexor pollicis longus, it divides into two branches, appearing between the medial and lateral attachments of the oblique head of adductor pollicis to run along both sides of the pollex, forming, on the palmar surface of its distal phalanx, a pollicial arch supplying the skin and subcutaneous tissue. The arterial princeps pollicis is the usual nutrient of supply to the first metacarpal bone.

Arteria radialis indicis (10.105, 109). Often a proximal branch of the arteria princeps pollicis, it descends between the first dorsal interosseous and transverse head of adductor pollicis, and along the lateral side of the index finger to its end; it anastomoses with the indicial medial digital artery. At the distal border of the transverse head of the adductor pollicis it anastomoses with the arteria princeps pollicis and links with the superficial palmar arch.

The arteriae princeps pollicis et radialis indicis may be combined as the *first palmar metacarpal artery*.

Deep palmar arch

This is formed by anastomosis of the end of the radial with the deep palmar branch of the ulnar artery (10.105). It crosses the bases of the metacarpal bones and interossei, covered by the oblique head of adductor pollicis, the digital flexor tendons and lumbricals. In its concavity, running laterally, is the deep branch of the ulnar nerve. The arch was incomplete in six of 200 arches (Coleman & Anson 1961). Variation is chiefly in the size of contribution from the ulnar artery.

Surface anatomy. The deep palmar arch is indicated by a horizontal line about 4 cm long from a point just distal to the hamate's hook (10.110). It is about 1 cm proximal to the superficial arch. **154**
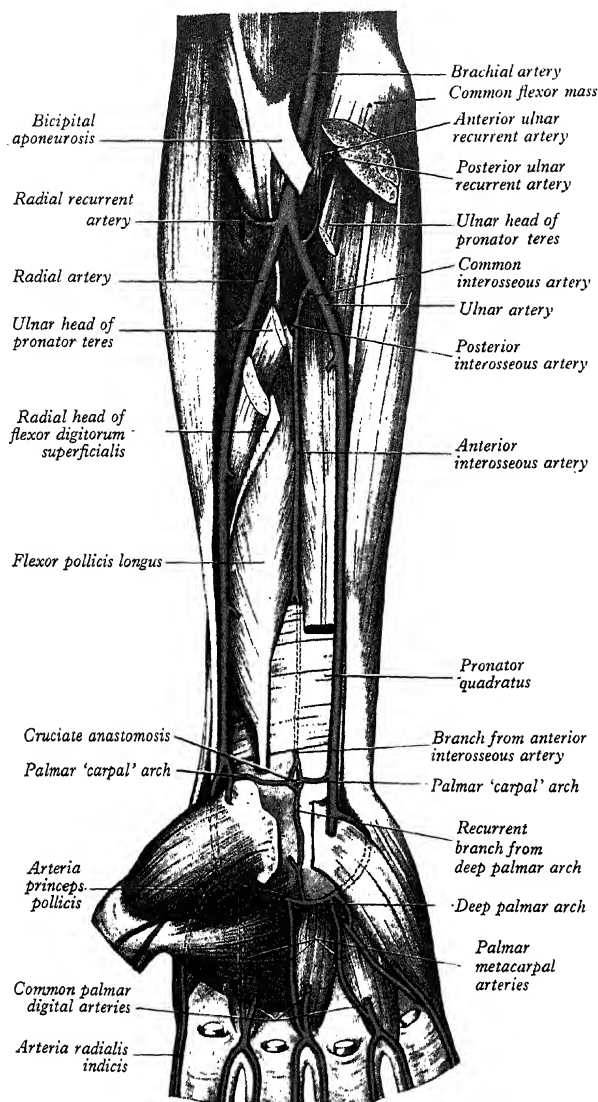
Branches of the deep palmar arch are the palmar metacarpal, perforating and recurrent.

Palmar metacarpal arteries (10.105). The three arteries run distally from the convexity of the arch on the interosseous muscles of the second to fourth spaces; at the digital clefts they join the *common digital branches* of the superficial arch. They supply nutrient branches to the medial four metacarpals.

Perforating branches. These three branches from the deep palmar arch traverse the second to fourth interosseous spaces between the heads of the corresponding dorsal interossei to anastomose with the dorsal metacarpal arteries.
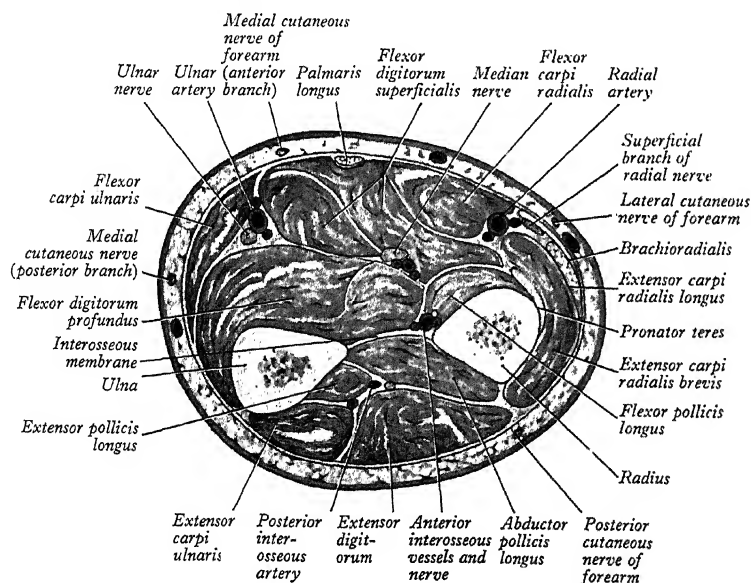
Recurrent branches (10.105). They ascend proximally from the deep palmar arch anterior to the carpus to supply the carpal bones and intercarpal articulations, ending in the palmar carpal arch (mentioned above).

The ulnar artery (10.102–109), the larger terminal branch of the brachial, begins just distal to the bend of the elbow. It reaches the medial side of the forearm midway between elbow and wrist, which it passes vertically, crossing the flexor retinaculum lateral to the ulnar nerve and pisiform bone; distal to this it has a deep branch and then continues across the palm as the superficial palmar arch.

Relations. In the forearm the **proximal half** of the artery (10.103–106) passes posterior to the pronator teres, flexor carpi radialis, palmaris longus and flexor digitorum superficialis; medially it is overlapped in its middle third by flexor carpi ulnaris; it lies in front of the brachialis and flexor digitorum profundus. Distal to the elbow the median nerve is medial for about 2.5 cm and then crosses it but is separated by the ulnar head of pronator teres. The artery's **distal half** (10.103, 105, 109) lies on the flexor digitorum profundus, covered by the skin, superficial and deep fasciae, between the flexor carpi ulnaris and flexor digitorum superficialis. It is accompanied by venae comitantes; the ulnar nerve lies medial to its distal two-thirds and its palmar cutaneous branch descends along it to the hand.

At the wrist (10.105, 107, 109) the artery is covered by skin, fasciae and palmaris brevis, and it lies between the superficial and main parts of the flexor retinaculum (p. 852); the ulnar nerve and pisiform bone are medial.

Surface anatomy. A line from a point in the limb's midline just distal to the elbow's fold descends medially to meet a line stretching from the medial epicondyle to the pisiform bone, from the junction of its upper and middle thirds. Together these represent the artery's upper third and distal two-thirds respectively.


10.105 The arteries of the right forearm and hand: deep dissection. The palmar 'carpal' arch lies across forearm bones.

10.106 Transverse section through the middle of the left forearm: proximal aspect.

Variations. The ulnar artery may arise proximal to the elbow, the brachial being more often its source than the axillary artery; it is then usually superficial to the forearm flexors, commonly under the deep fascia, and is rarely subcutaneous; the brachial artery then supplies the common interosseous and this the ulnar recurrent arteries.

Branches. The artery supplies medial muscles in the forearm and hand, the common flexor synovial sheath and ulnar nerve (Blunt 1959), including the following named branches:

Anterior ulnar recurrent artery (10.102, 105). This arises just distal to the elbow, ascends between the brachialis and pronator teres, supplies them and anastomoses with the inferior ulnar collateral artery anterior to the medial epicondyle.

Posterior ulnar recurrent artery (10.102, 105). A larger artery, it arises distal to the anterior recurrent, and passes dorsomedially between the flexores digitorum profundus and superficialis, ascending behind the medial epicondyle; between this and the olecranon it is deep to the flexor carpi ulnaris, ascending between its heads with the ulnar nerve. Supplying adjacent muscles, nerve, bone and elbow joint, it anastomoses with the ulnar collateral and interosseous recurrent arteries (**10.102**).
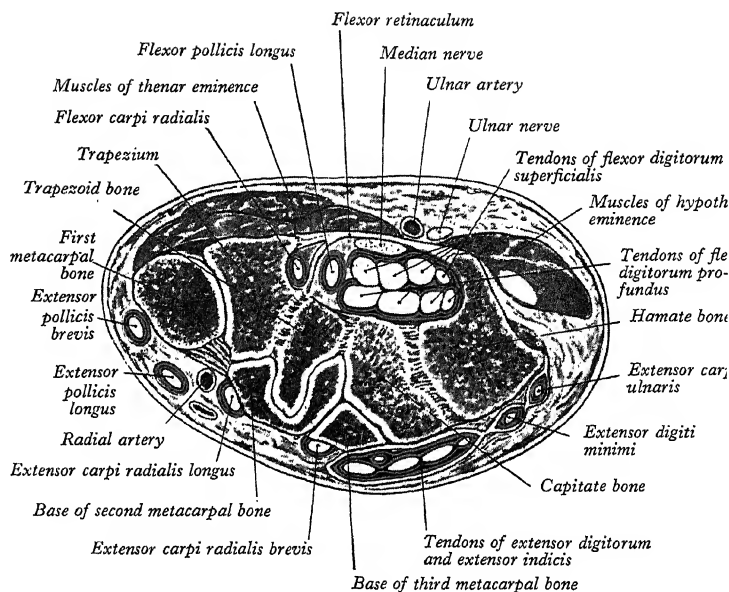
10.107 Transverse section through the left wrist: proximal aspect. The section is slightly oblique and divides the distal row of the carpus and the bases of the first, second and third metacarpal bones. The arrangement of the tendons of the flexors of the fingers shown in the figure represents the actual condition in the specimen. Observe that the carpometacarpal joint of the thumb is separate from the joint between the trapezium and the base of the second metacarpal bone.
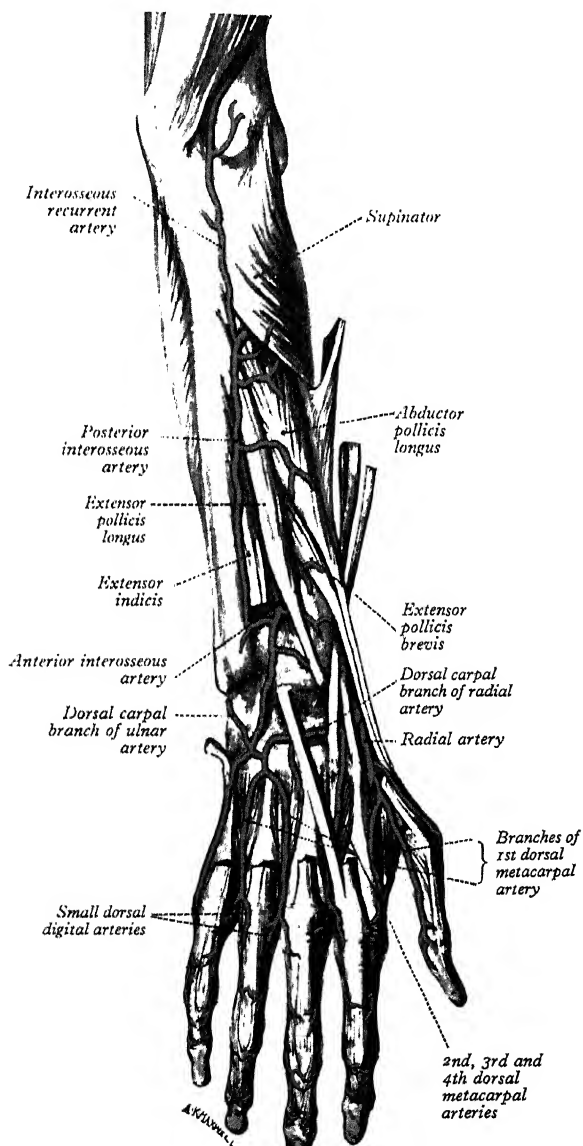

10.108 The arteries of the posterior surface of the right forearm and hand.

Common interosseous artery (10.102, 105). A short branch of the ulnar, just distal to the radial tuberosity, it passes back to the proximal border of the interosseous membrane, dividing into the *anterior* and *posterior interosseous arteries.*

Anterior interosseous artery (10.102, 105). Descending on the anterior aspect of the interosseous membrane with the median nerve's anterior interosseous branch, it is overlapped by contiguous sides of flexor digitorum profundus and flexor pollicis longus; it has *muscular branches* and *nutrient branches* for the radius and ulna. On the membrane, branches leave to pierce it and supply deep extensor muscles. Proximal to pronator quadratus its continuation also traverses the membrane to the back of the forearm where it anastomoses with its own posterior interosseous branch, descending over the carpal dorsum to join the dorsal carpal arch. It is in the extensor retinacular compartment with the tendons of digital extensors. Before it pierces the interosseous membrane, a branch descends behind the pronator quadratus to the anterior 'carpal' arch. (Strictly, as mentioned, the latter is **proximal** to the line of the wrist joint.) The slender *median artery*, from the start of the anterior interosseous, accompanies and supplies the median nerve; it often arises from the common interosseous, sometimes much enlarged, reaching the palm with the nerve (p. 319), where it may join the superficial palmar arch or end as one or two palmar digital arteries.

Posterior interosseous artery (10.105, 108). Usually smaller than the anterior, it passes dorsally between the oblique cord and proximal border of the interosseous membrane and then between supinator and abductor pollicis longus, descending deep to the superficial extensors, which it supplies. On abductor pollicis longus it accompanies the deep branch of the radial nerve. Distally it anastomoses with the end of the anterior interosseous and dorsal carpal arch. Near its origin the *interosseous recurrent artery* leaves it to ascend between the lateral epicondyle and olecranon, either on or through the supinator but deep to anconeus, to anastomose with the middle collateral branch of the arteria profunda brachii, posterior ulnar recurrent and ulnar collateral arteries.

Muscular branches. These arise directly from the main vessel and distribute to muscles in the ulnar region.
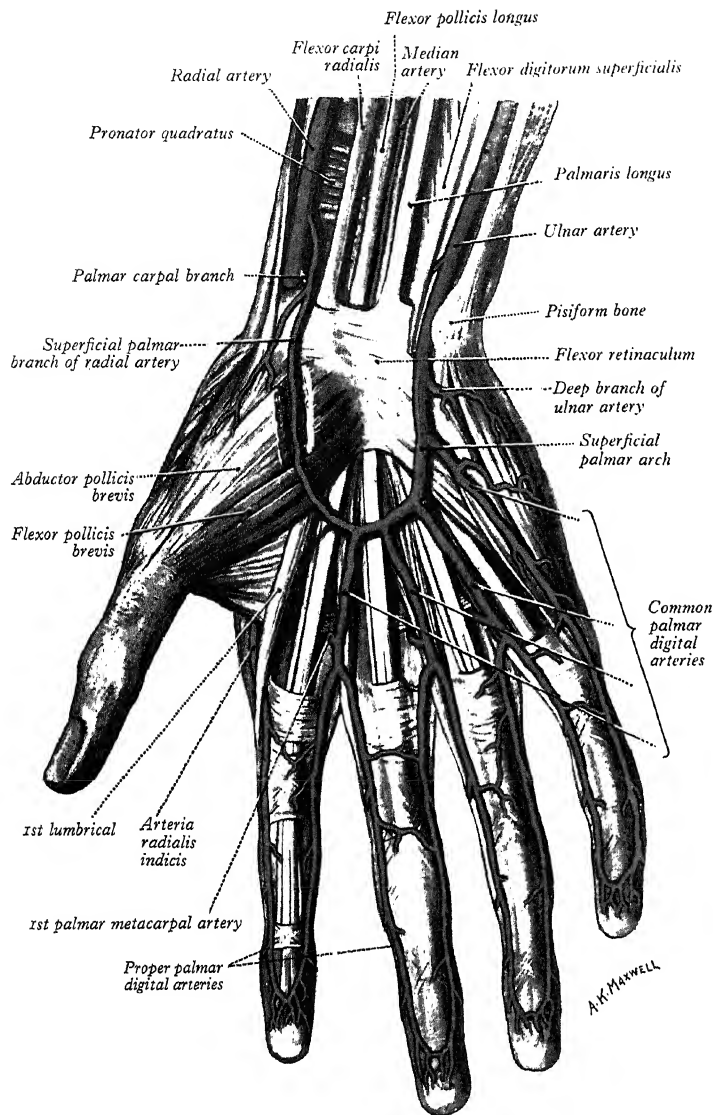
10.109 The superficial palmar arch and its branches in the right hand. A part of the abductor pollicis brevis has been excised to expose the superficial palmar branch of the radial artery.
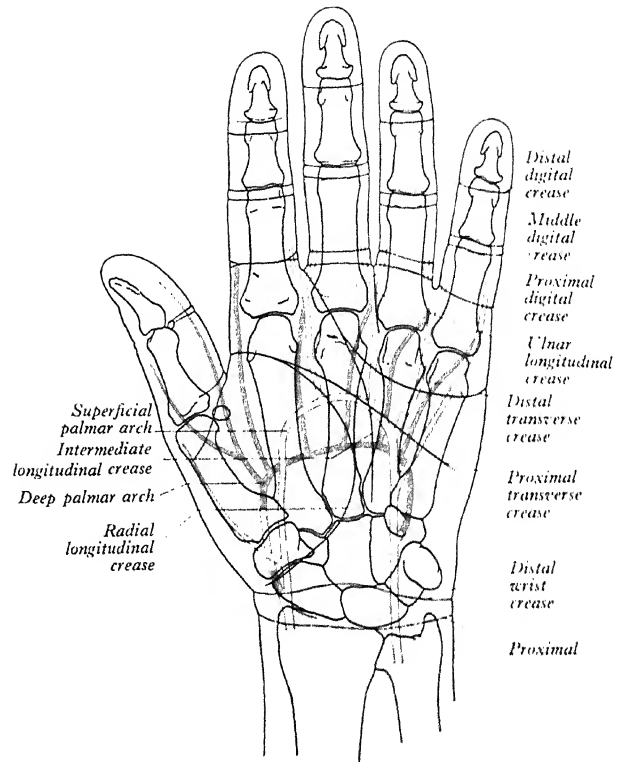

10.110 The relation of the skin flexure lines and palmar arterial arches to the bones of the left hand (simplified).

Palmar carpal branch (10.105). A small vessel, it crosses the distal ulna behind the tendons of flexor digitorum profundus; it anastomoses with a palmar carpal branch of the radial to make a so-called palmar carpal arch (p. 1541).

Dorsal carpal branch (10.108). Arising just proximal to the pisiform bone, it curves deep to the tendon of flexor carpi ulnaris to the carpal dorsum to pass laterally across it under the extensor tendons, anastomosing with the radial dorsal carpal branch to complete the dorsal carpal arch (p. 1541). Near its origin it sends a small digital branch along the ulnar side of the fifth metacarpal to supply the medial side of the dorsal surface of the fifth finger.

Deep palmar branch (10.105, 109). Often double, it passes between the abductor and flexor digiti minimi, through or deep to the opponens digiti minimi; it anastomoses with the radial, completing the deep palmar arch, accompanied by the deep branch of the ulnar nerve.

Superficial palmar arch (10.109, 110)

This anastomosis is fed mainly by the ulnar artery, entering the palm with the ulnar nerve, anterior to the flexor retinaculum and lateral to the pisiform, passing medial to the hamate's hook, then curving laterally to form an arch, convex distally and level with a transverse line through the distal border of the fully extended pollicial base. About a third of the superficial palmar arches are formed by the ulnar alone; a further third are completed by the superficial palmar branch of the radial and a third either by the arteria radialis indicis, a branch of arteria princeps pollicis or by the median artery (Coleman & Anson 1961). It is covered by the palmaris brevis and palmar aponeurosis and it is superficial to the flexor digiti minimi, branches of the median nerve and to the long flexor tendons and lumbrical muscles.

Branches. Three common palmar digital arteries (**10.109**) from the convexity of the superficial palmar arch proceed distally on the second to fourth lumbricals, each joined by a corresponding palmar metacarpal artery from the deep palmar arch and dividing into two *proper palmar digital arteries.* These run along the contiguous sides of all four fingers, dorsal to the digital nerves, anastomosing in the subcutaneous tissue of the finger tips and near the interphalangeal joints. Each digital artery has two *dorsal branches* anastomosing with the *dorsal digital arteries* and supplying the soft parts dorsal to the middle and distal phalanges, including the matrices of the nails. The *palmar digital artery* for the medial side of minimus leaves the arch under the palmaris brevis. Palmar digital arteries supply metacarpophalangeal and interphalangeal joints and nutrient rami to the phalanges. They are the main digital supply, the dorsal digital arteries (p. 1541) being minute.

Anastomoses between the radial and ulnar arteries occur:

- at the wrist by the palmar and dorsal carpal arches
- in the hand through the superficial and deep palmar arches
- between their digital and metacarpal branches.

Wounds of the palmar arches. Ligature of **one** forearm artery may be ineffective in wounds of the palmar arches; simultaneous tying of both proximal to the carpus may also fail, because of interosseo-carpal anastomoses. If local pressure fails the brachial artery may be compressed (p. 1538) as a temporary expedient.

The thoracic aorta (10.111) is the segment of *descending aorta* confined to the posterior mediastinum. It begins level with the fourth thoracic vertebra's lower border, continuous with the aortic arch, ending anterior to the twelfth thoracic's lower border in the diaphragmatic aortic aperture. At its origin it is left of the vertebral column; as it descends it approaches the midline and at its termination is directly anterior to it.

Relations. Anterior, from above down, are the left pulmonary hilum, the pericardium separating it from the left atrium, oesophagus and diaphragm; posterior are the vertebral column and hemiazygos veins; right lateral are the azygos and thoracic duct and below, the right pleura and lung; left lateral are the pleura and lung. The oesophagus, with its plexus of nerves, is right lateral above but becomes anterior in the lower thorax; close to the diaphragm it is left anterolateral. Thus, to a limited degree, the descending aorta and oesophagus are mutually spiralized.

Surface anatomy. The vessel is projected as a band 2.5 cm broad from the sternal end of the second left costal cartilage to a median position about 2 cm above the transpyloric plane (p. 1733).

Branches. The thoracic aorta provides visceral branches to the pericardium, lungs, bronchi, oesophagus and parietal branches to the thoracic wall.
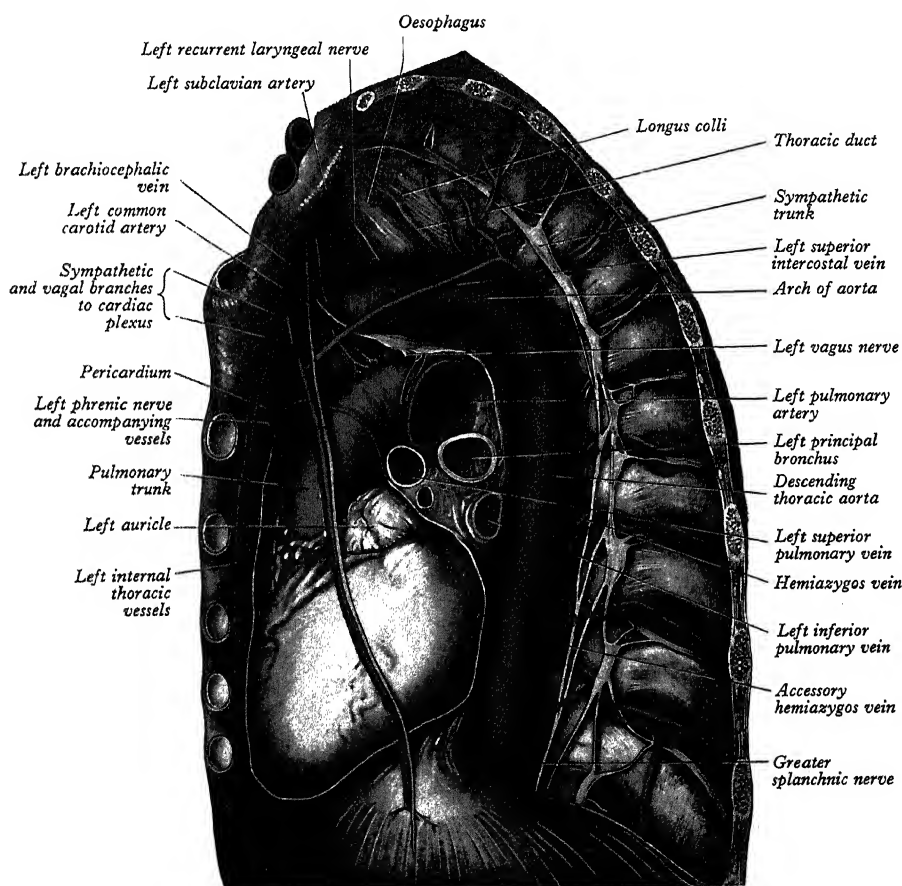
Pericardial branches. A few small vessels: they are distributed to the posterior pericardial aspect.

Bronchial arteries. These vary in number, size and origin. Usually one *right bronchial artery*, from the third posterior intercostal or upper left bronchial artery, runs posteriorly on the right bronchus and its branches, supplying them, the pulmonary areolar tissue and the bronchopulmonary lymph nodes, pericardium and oesophagus. The *left bronchial arteries*, usually two, arise from the thoracic aorta, the upper near the fifth thoracic vertebra, the lower below the left bronchus. They run posteriorly to the left bronchus and are distributed as on the right. Cauldwell et al (1948) found this arrangement in 40% of 150 cadavers; less frequent (at about 20% each) were two left and two right bronchial arteries or one on each side, all direct branches of the thoracic aorta, arising near the third and fourth intercostal arteries. In about 10%, one left and two right bronchial arteries existed. Complex variations consisted chiefly of more numerous aortic branches. Very rarely a bronchial artery arose from the aortic arch.

Oesophageal arteries. These are four or five, which arise anteriorly from the aorta and descend obliquely to the oesophagus, forming a vascular chain on it which anastomoses above with the oesophageal branches of the inferior thyroid arteries and below with the ascending branches from the left phrenic and gastric.

Mediastinal branches. These are numerous small vessels supplying lymph nodes and areolar tissue in the posterior mediastinum.

Phrenic branches. These arise from the lower thoracic aorta and are distributed posteriorly to the superior diaphragmatic surface and anastomose with the musculophrenic and pericardiacophrenic arteries.

Oesophagus

Left recurrent laryngeal nerve

Left subclavian artery

Left brachiocephalic vein

Left common carotid artery

Sympathetic and vagal branches to cardiac plexus

Pericardium

Left phrenic nerve and accompanying vessels

Pulmonary trunk

Left auricle

Left internal thoracic vessels

Longus colli

Thoracic duct

Sympathetic trunk

Left superior intercostal vein

Arch of aorta

Left vagus nerve

Left pulmonary artery

Left principal bronchus

Descending thoracic aorta

Left superior pulmonary vein

Hemiazygos vein

Left inferior pulmonary vein

Accessory hemiazygos vein

Greater splanchnic nerve

10.111 The left aspect of the mediastinum. The left lung and pleura have been removed and an extensive opening has been made into the pericardial sac to expose the heart. Note the oblique orientation of the thoracic inlet, and the forward inclination of the longus colli, upper oesophagus and thoracic duct.

Posterior intercostal arteries

Usually nine pairs of posterior intercostal arteries derive from the posterior aspect of the descending thoracic aorta. They are distributed to the lower nine intercostal spaces, the first and second being supplied by the superior intercostal artery (p. 1535). *Right posterior intercostal arteries* are longer, due to aortic deviation to the left; they cross the vertebral bodies behind the oesophagus, thoracic duct and azygos vein, right lung and pleura. *Left posterior intercostal arteries* turn backwards on the vertebral bodies in contact with the left lung and pleura, the upper two crossed by the left superior intercostal vein, the lower by the hemiazygos and accessory hemiazygos veins. Their further course is the same on both sides. Anterior to the heads of the ribs the sympathetic trunk descends in front of them and additionally the splanchnic nerves in front of the lower arteries.

Each artery crosses its intercostal space obliquely towards the angle of the rib above and continues forward in its costal groove (10.111). At first between the pleura and internal (posterior) intercostal membrane as far as the costal angle, it passes between the intercostalis internus and intercostalis intimus muscles (p. 815), anastomosing with an anterior intercostal branch from an internal thoracic or musculophrenic artery. It has a vein above and a nerve below, except in the upper spaces where the nerve is at first above the artery. The third anastomoses with the superior intercostal artery and may largely supply the second space. The lower two arteries continue anteriorly into the abdominal wall to anastomose with the subcostal, superior epigastric and lumbar arteries. Each posterior intercostal artery has dorsal, collateral, muscular and cutaneous branches.

Dorsal branch. This runs dorsally between the necks of adjoining ribs, with a vertebral body and a superior costotransverse ligament lying medial and lateral, respectively. It has a spinal branch entering the vertebral canal by the intervertebral foramen to supply vertebrae, spinal cord and meninges; it anastomoses with the spinal arteries above and below and with its fellow. It then crosses a transverse process with the dorsal branch of a thoracic spinal nerve to supply the dorsal muscles; a cutaneous twig accompanies the cutaneous branch of the spinal nerve's dorsal ramus.

Collateral intercostal branch. It leaves its posterior intercostal near the costal angle and descends to the upper border of the subjacent rib, along which it courses to anastomose with an anterior intercostal branch of the internal thoracic or musculophrenic artery.

Muscular branches. These supply intercostal and pectoral muscles and the serratus anterior, anastomosing with the superior and lateral thoracic branches of the axillary artery. Lateral cutaneous branches accompany the same branches of the thoracic spinal nerves. Mammary branches from the vessels in the second to fourth spaces supply the pectoral muscles, skin and mammary tissue; they enlarge during lactation.

Unnamed branches. They supply all other tissues constituting the thoracic wall, e.g. costal periosteum, bone and bone marrow of ribs, tissues of synovial and synarthrodial joints and parietal pleura.

Right bronchial artery. It may arise from the right third posterior intercostal artery (see above).

Clinical anatomy. A thoracic puncture needle should not be introduced posteriorly medial to the costal angles, as the intercostal artery (and vein) crosses its space medial to this. Laterally, however, it is in the upper part of its intercostal space; therefore puncture should be through the **lateral** chest wall in the *lower* half of a space.

Subcostal arteries. The last paired branches of the thoracic aorta, in series with the posterior intercostal arteries, they are below the twelfth ribs. Each runs laterally anterior to the twelfth thoracic vertebral body and posterior to the splanchnic nerves, sympathetic trunk, pleura and diaphragm; the right is also posterior to the thoracic duct and azygos vein, the left to the accessory hemiazygos vein. Each then enters the abdomen posterior to the lateral arcuate ligament with the twelfth thoracic (subcostal) nerve at the lower border of the twelfth rib, anterior to quadratus lumborum and posterior to the kidney. The right artery courses posterior to the ascending colon, the left to its descending part. Piercing the aponeurosis of the transversus abdominis each proceeds between this and the obliquus internus, anastomosing with the superior epigastric, lower posterior intercostal and lumbar arteries. Each has a dorsal branch, distributed like those of the posterior intercostal arteries.

Aberrant artery. A small artery sometimes leaves the thoracic aorta on its right near the right bronchial. It ascends to the right behind the trachea and oesophagus and may anastomose with the right superior intercostal. It is a vestige of the right dorsal aorta (p. 316); occasionally it is enlarged as the first part of a right subclavian (p. 1530).

VARIATIONS OF THORACIC AORTA

The aortic lumen is occasionally partly or completely obliterated, above (preductal or infantile type), opposite or just beyond (postductal or adult type) the entry of the ductus arteriosus. The condition, *coarctation of the aorta*, is congenital; the ductus arteriosus may remain patent, but rarely compensates, systemic blood pressure being usually much higher than pulmonary.

In the *preductal* type, the coarctation's length is variable and may involve the left subclavian and even the brachiocephalic artery, with little scope for the development of an effective collateral circulation to regions distal to the stenosis. Many cases are incompatible with survival for more than a few months and surgical problems are great. However, coarctation may be restricted to a short segment between the brachiocephalic and left subclavian arteries, pressures in the left arm being lower than in the right; a collateral circulation may develop through branches of the brachiocephalic.

The *postductal* type of coarctation has been attributed to abnormal extension of the ductal tissue into the aortic wall, stenosing both vessels as the duct contracts after birth. This form can permit many years of normal life, allowing the development of an extensive collateral circulation to the aorta distal to the stenosis. High vascularity of the thoracic wall is important and clinically characteristic; many arteries arising indirectly from the aorta, proximal to the coarctation segment, anastomose with vessels connected with it distal to the block; these become greatly enlarged. In the anterior thoracic wall the thoraco-acromial, lateral thoracic and subscapular arteries from the axillary, the suprascapular from the subclavian and the first and second posterior intercostal arteries from the costocervical trunk anastomose with other posterior intercostal arteries; the internal thoracic artery and its terminal branches anastomose with the lower posterior intercostal and inferior epigastric arteries. Posterior intercostal arteries are always involved, and enlargement of their dorsal branches may eventually groove ('notch') the inferior margins of the ribs. The radiograph shadow of the enlarged left subclavian artery is also increased. Enlargement of the scapular vessels and anastomoses may lead to widespread interscapular pulsation (easily appreciated with the palm of the hand, and sometimes heard on auscultation).

The abdominal aorta (**10**.112, 113, 115, 128) begins at the median, aortic hiatus of the diaphragm, anterior to the twelfth thoracic vertebra's inferior border and the thoracolumbar intervertebral symphysis ('disk'), descending anterior to the vertebrae to end at the fourth lumbar, a little left of the midline, by dividing into two common iliac arteries. It diminishes rapidly in calibre, since its branches are large. Measurements of casts of the abdominal aorta in 100 individuals, from 16–70 years, showed a widening with age. In males superior and inferior ends measured 9.8–14.1 mm and 8.1–14.6 mm; in females luminal diameters were 9.7–15.7 mm and 9.1–14.6 mm (Aleksandrowicz et al 1974). These values conflict with radiological observation of 61 adults (17–41 years) by Leithner et al (1975), who recorded 26 mm and 19 mm (averages) for both ends of the abdominal aorta; they also gave a mean value of 37 for the angle of aortic bifurcation. Dimensions are of interest in attempts to estimate a suspected hydrodynamic ('haemodynamic') factor in the genesis of atherosclerosis (Newman et al 1971; Lallemand & Newman 1973). Theoretically, the pressure pulse wave in arteries is reflected at any junction, at certain values of combined arterial luminal areas of the branch or branches relative to that of the parent vessel; this is the area ratio of a junction. At an equal bifurcation, such as the aortic, with an area ratio of 1:1.5, reflection of the pressure pulse wave is near to zero; the vessels are said to be 'matched'. Oscillations and possibly turbulence set up by 'mismatching' (at other ratios), perhaps also influenced by asymmetry of bifurcation, may cause intimal damage, predisposing to aortic atheroma. Luminal and other dimensions of the bifurcation may assume special significance, as may changes in these during life. Measurement of aortico-iliac junctions in humans, dogs and domestic fowls (free from vascular disease) has shown area ratios usually close to the theoretical value for 'matching' and independent of age in dog and fowl (Gosling et al 1971). However, the human aortic bifurcation appears to be 'matched' only in infancy; it is 1.11 ± 0.02 at birth, diminishing with advancing age to a value of about 0.7 in the fifth decade, at which theory predicts a 'mismatch' reflecting pulse pressure wave at about one-third of its amplitude. These studies give special interest to a

study of the geometry of aortic bifurcation by Shah et al (1978), containing the most extensive data so far recorded, including diameters and angles of deviation, iliac lengths and curvatures and dorsal angulations of these vessels as they enter the pelvis. Unfortunately, diameters were external and only on a small series of cadavers at autopsy, and cannot be compared with those cited above. These interesting observations should be carried further with improved techniques and greater cohesion between different groups involved.
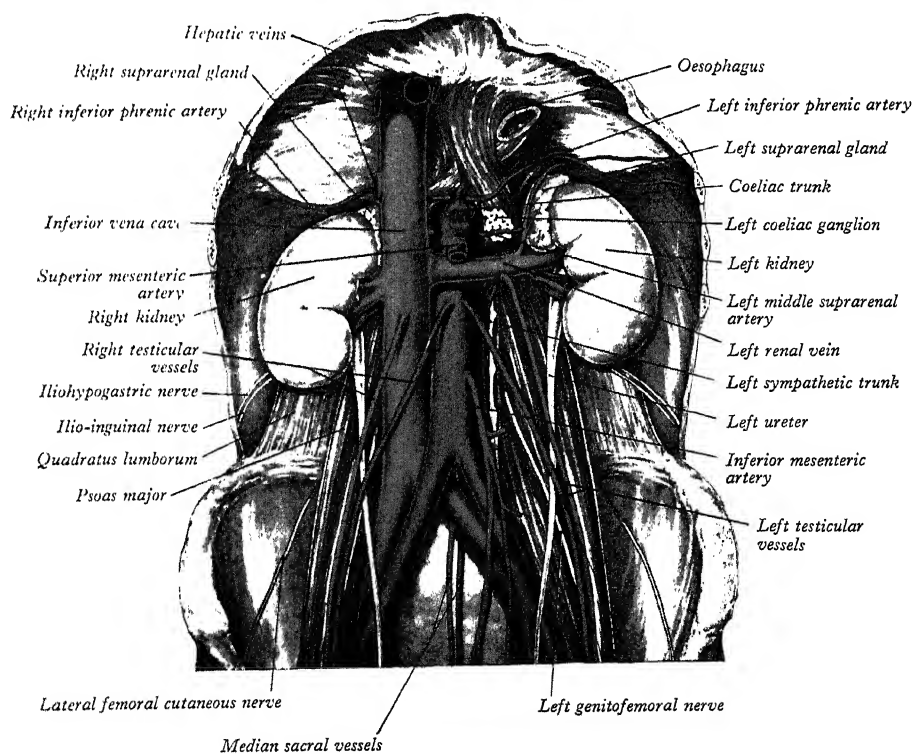
Relations. The abdominal aorta has at first **anterior** to it the coeliac trunk and its branches, with the coeliac plexus and the lesser sac (omental bursa) which intervenes between it and the hepatic papillary process and lesser omentum. Below this the superior mesenteric artery leaves the aorta, crossing anterior to the left renal vein. The body of the pancreas, with splenic vein applied posteriorly, extends obliquely up and left across the abdominal aorta, separated from it by the superior mesenteric artery and left renal vein. Below the pancreas, the proximal parts of its testicular (or ovarian) arteries, and the horizontal part of the duodenum are anterior. In its lowest part it is covered by the posterior parietal peritoneum and crossed by the oblique parietal attachment of the mesentery.
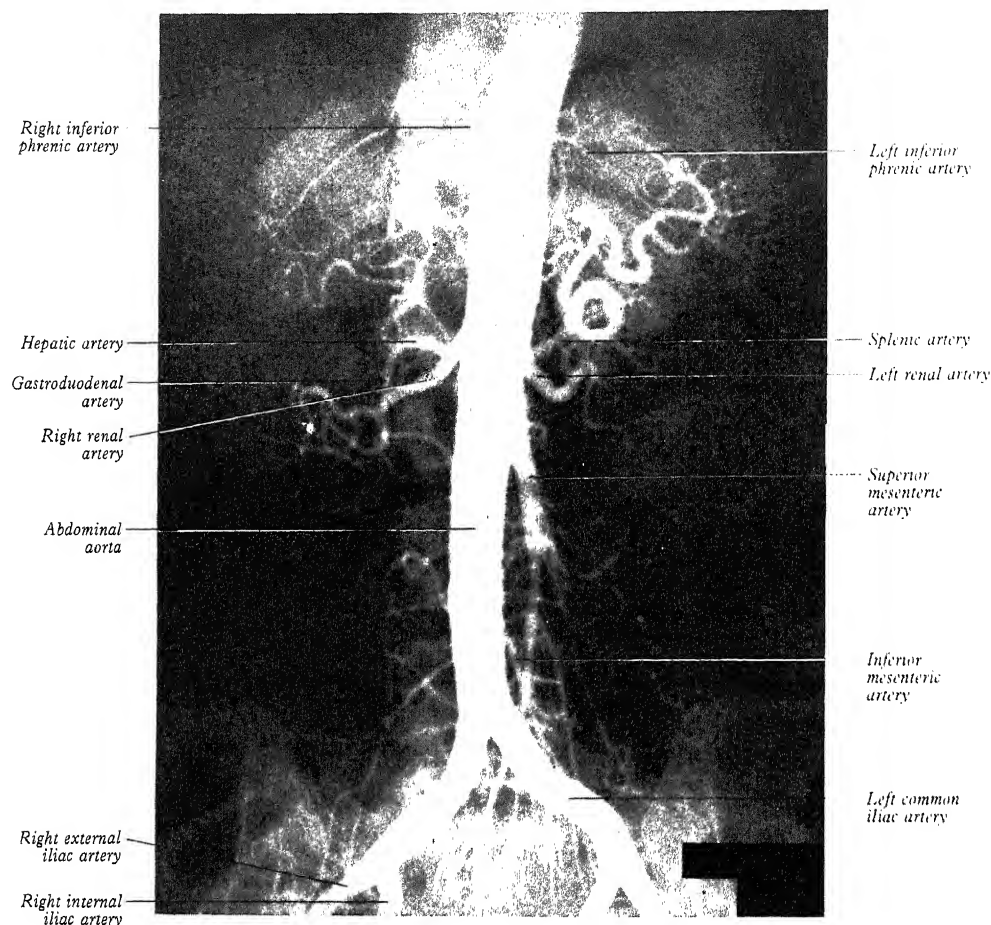
Posterior to the abdominal aorta are the thoracolumbar intervertebral 'disk', the upper four lumbar vertebrae, intervening intervertebral discs and the anterior longitudinal ligament. Lumbar arteries, arising from its dorsal aspect, and the third and fourth (sometimes second) left lumbar veins, crossing behind it to reach the inferior vena cava, separate it from the ligament. It may overlap the anterior border of the left psoas major.

On the right the aorta is related above to the cisterna chyli and thoracic duct, azygos vein and right crus of diaphragm, which overlaps and separates it from the inferior vena cava and right coeliac ganglion. Below the second lumbar vertebra it adjoins the inferior vena cava.

On the left it is related above to the left diaphragmatic crus and left coeliac ganglion. Level with the second lumbar vertebra are the duodenojejunal flexure and sympathetic trunk descending, at its left side, and the ascending duodenum and inferior mesenteric vessels.

Surface anatomy. The vessel is indicated by a band about 2 cm wide from a median level 2.5 cm above the transpyloric plane to one about 1 cm below and left of the umbilicus. When the abdominal wall

Hepatic veins

Right suprarenal gland

Right inferior phrenic artery

Oesophagus

Left inferior phrenic artery

Left suprarenal gland

Coeliac trunk

Left coeliac ganglion

Inferior vena cava

Superior mesenteric artery

Right kidney

Left kidney

Left middle suprarenal artery

Right testicular vessels

Left renal vein

Iliohypogastric nerve

Left sympathetic trunk

Ilio-inguinal nerve

Left ureter

Quadratus lumborum

Inferior mesenteric artery

Psoas major

Left testicular vessels

Lateral femoral cutaneous nerve

Left genitofemoral nerve

Median sacral vessels

10.112 The abdominal aorta and its branches in the male.

Right inferior phrenic artery

Hepatic artery

Gastroduodenal artery

Right renal artery

Abdominal aorta

Right external iliac artery

Right internal iliac artery

Left inferior phrenic artery

Splenic artery

Left renal artery

Superior mesenteric artery

Inferior mesenteric artery

Left common iliac artery

10.113 Aorto-iliac angiogram. (Supplied by Shaun Gallagher, Guy's Hospital; photography by Sarah Smith.)

is relaxed the aorta may be felt pulsating just above its bifurcation and its pulsation may be visible. This is frequently the case in thin subjects. An easily palpable aorta in someone who is obese should raise the suspicion of an aneurysm, to be checked by ultrasound scan.

Branches (10.112, 113). These may be described as ventral, lateral, dorsal and terminal; ventral and lateral are distributed to the viscera, the dorsal branches supplying the body wall, vertebral column, canal and its contents:

Ventral: Coeliac, superior and inferior mesenteric
Dorsal: Lumbar and median sacral
Lateral: Inferior phrenic, middle suprarenal, renal, ovarian or
        testicular
Terminal: Common iliac.

COELIAC TRUNK

The coeliac trunk (10.114–117), a wide ventral branch, about 1.25 cm long, just below the aortic hiatus, passes almost horizontally forwards and slightly right above the pancreas and splenic vein, dividing into:

- *left gastric*
- *common hepatic*
- *splenic arteries.*

It may also give off one or both inferior phrenic arteries. The superior mesenteric may arise with the coeliac trunk, or the latter's usual branches may be direct independent branches of the aorta.

Relations. **Anterior** is the omental bursa (lesser sac); the coeliac plexus surrounds the trunk, sending extensions along its branches.

Right lateral are the right coeliac ganglion, right crus and hepatic caudate process; **left lateral** are the left coeliac ganglion, left crus and cardiac end of the stomach. The right crus may compress the origin of the coeliac trunk, giving the appearance of a stricture. Symptoms have been attributed to this (the 'coeliac axis compression syndrome'), and operations designed to relieve it, but the concept is of doubtful validity. **Inferior** are the pancreas and splenic vein. The duodenum's suspensory muscle (p. 1763) may encircle the coeliac artery but is usually on its left.

Left gastric artery

The left gastric artery, the smallest coeliac branch, ascends to the left, posterior to the omental bursa, to the cardiac end of the stomach (10.114, 115). It is near the left inferior phrenic artery and medial or anterior to the left suprarenal gland. Near the stomach two or three *oesophageal branches* ascend through the oesophageal opening to anastomose with the aortic oesophageal branches; others supply the cardiac part of the stomach and anastomose with the splenic branches. The artery then turns antero-inferiorly into the left gastro-pancreatic fold to run (often doubled) curving to the right near the gastric lesser curvature to the pylorus between layers of the lesser omentum; it supplies both gastric surfaces and anastomoses with the right gastric artery. An *accessory left gastric* artery may arise from the left branch of the hepatic, also reaching the lesser curvature through the lesser omentum.

Hepatic artery

The hepatic artery is intermediate in size between the left gastric and splenic arteries; but in later fetal and early postnatal life it is the largest coeliac branch (10.114–116, 118). Accompanied by the hepatic autonomic plexus it first passes forwards and right, below the epiploic
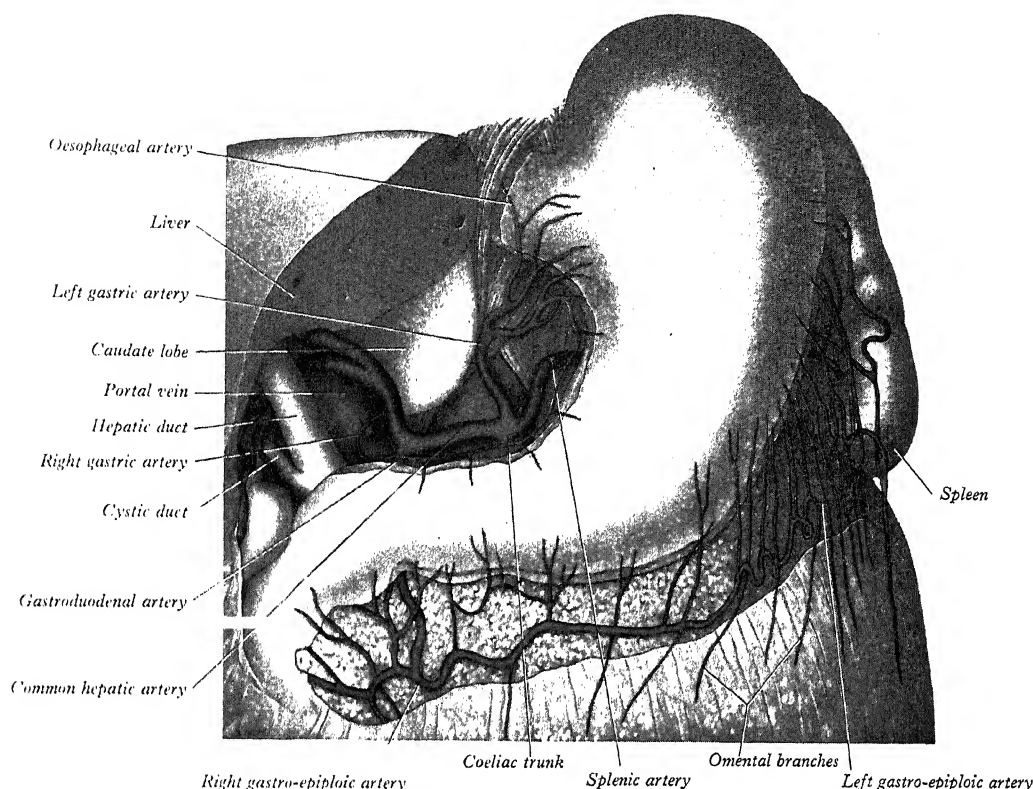
10.114 The coeliac trunk and its branches. Part of the liver and all the lesser omentum have been removed, as well as the posterior wall of the omental bursa and part of the anterior layer of the greater omentum.

foramen to the upper aspect of the superior part of the duodenum (10.114). Crossing the portal vein, it ascends between layers of the lesser omentum, anterior to the epiploic foramen, to the porta hepatis, where it divides into right and left branches to the hepatic lobes, accompanying the ramifications of the portal vein and hepatic ducts. In the lesser omentum it is anterior to the portal vein and left of the bile duct, its right branch crossing posterior (occasionally anterior) to the common hepatic duct (10.115). The artery may be subdivided into:

• the *common hepatic artery*, from the coeliac trunk to the origin of the gastroduodenal artery
• the *hepatic artery proper*, from that point to its bifurcation.

In embryonic and early fetal life, the hepatic artery arises from the left gastric (in 67% of 56 individuals; Godlewski et al 1975). This condition rarely persists, but the hepatic may arise from the superior mesenteric, or the hepatic's right or left branches may be from other vessels; the former from the superior mesenteric, the latter from the left gastric. For other variations consult Quain (1865, 1899) and Woodburne (1962) (see also pp. 1550, 1810). The hepatic artery has right gastric, gastroduodenal and cystic branches, branches to the bile duct from the right hepatic and sometimes the supraduodenal artery (see below).

Right gastric artery (10.114). It arises above the duodenum's superior part, usually before, or sometimes beyond the gastroduodenal, descending in the lesser omentum to the pyloric end of the stomach; it passes left along the lesser gastric curvature, supplying the upper parts of the anterior and posterior gastric surfaces. It ends by anastomosing with the left gastric; the supraduodenal artery may be a branch (see below).

Gastroduodenal artery (10.114–116). Arising behind, sometimes above, the superior part of the duodenum, it is short and wide. It descends between the duodenum and the neck of the pancreas, immediately to the right of the peritoneal reflection from the posterior duodenal surface. It is usually left of the bile duct but sometimes

anterior. At the lower border of the duodenum's superior part it divides into the *right gastro-epiploic* and *superior pancreaticoduodenal* arteries, after supplying small branches to the pyloric end of the stomach and to the pancreas, retroduodenal branches to the superior part of the duodenum, and sometimes providing the supraduodenal artery (see below). The first branch of the common hepatic artery is usually the gastroduodenal artery, but this may come from the superior mesenteric, coeliac trunk or an aberrant right hepatic artery (p. 1552); its most invariable feature is its intermediate position between the **neck** of the pancreas and the duodenum, this being clinically important due to its frequent involvement in duodenal ulceration (Bradley 1973).

The *supraduodenal artery*, sometimes double, is variable; it may arise from the gastroduodenal, hepatic (common, proper or the latter's branches) or from the right gastric artery. It supplies the superior half circumference of the proximal half or more of the duodenum's superior part; but the duodenum is often invaded proximally by branches of the right gastric artery (p. 1765).

Right gastro-epiploic artery (10.114, 115, 118). The larger terminal branch of the gastroduodenal, it skirts the right margin of the omental bursa and then turns left along the greater curvature, between the (anterior two) layers of the greater omentum. It ends in direct anastomosis with the left gastro-epiploic branch of the splenic. Except at the pylorus, where it adjoins the stomach, it is about 2 cm from the greater curvature. Of its many branches some ascend to both gastric surfaces, others descend into the greater omentum. It also supplies the inferior aspect of the duodenum's superior part.

Superior pancreaticoduodenal arteries (10.115). These are usually double: the *anterior* descends anteriorly between the duodenum and head of the pancreas. It supplies both, and anastomoses with the anterior division of the inferior pancreaticoduodenal branch of the superior mesenteric. The *posterior superior pancreaticoduodenal artery*, which is usually a separate branch of the gastroduodenal arising at the upper border of the superior part of the duodenum, descends to the right, anterior to the portal vein and bile duct and
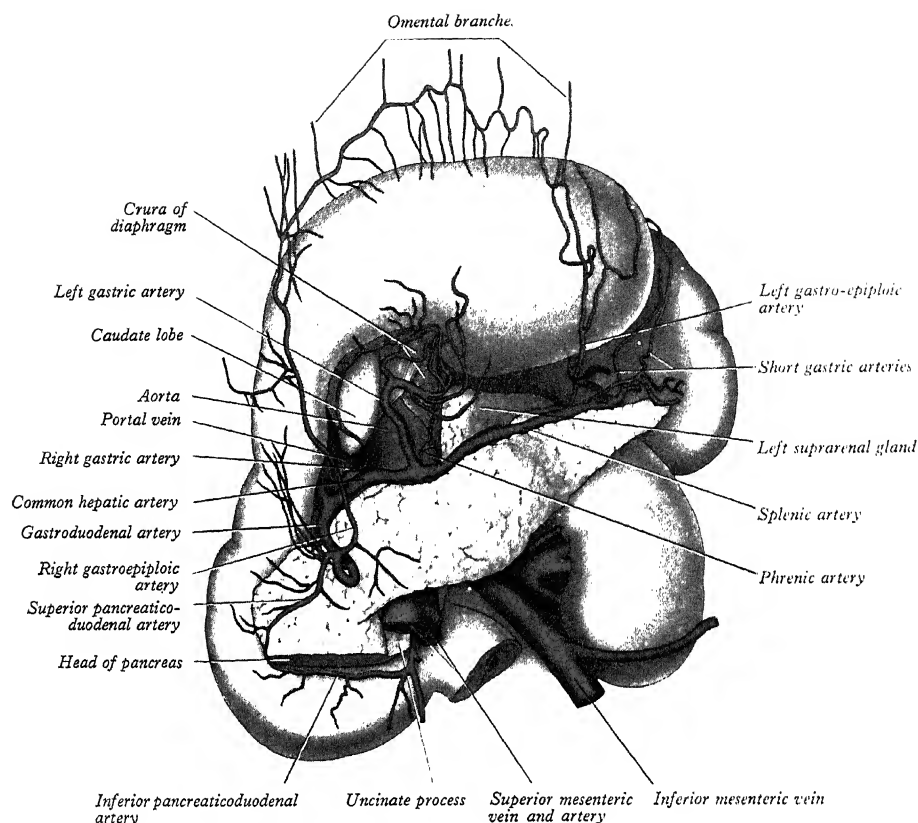
10.115 The coeliac trunk and its branches exposed by turning the stomach upwards and removing the peritoneum on the posterior abdominal wall.

then posterior to the head of the pancreas, supplying branches to it and the duodenum; it crosses posterior to the bile duct, piercing the duodenal wall to end by anastomosing with the posterior division of the inferior pancreaticoduodenal artery. The artery supplies several branches to the lower part of the common bile duct (p. 1810).
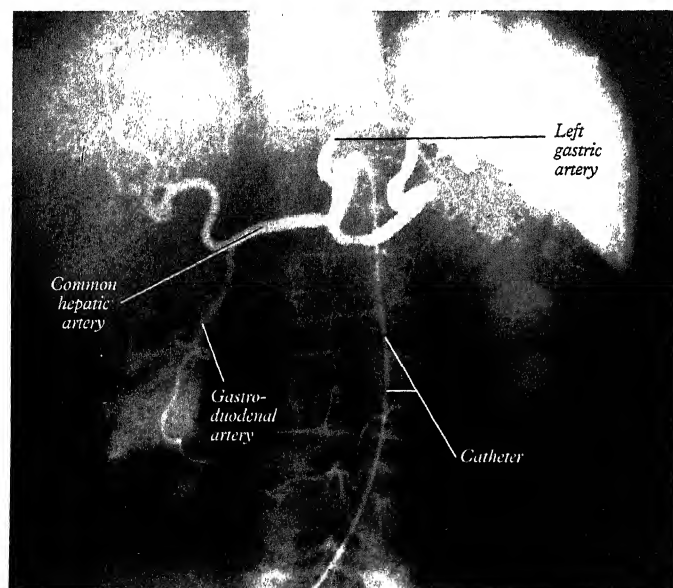
1550 **10.116** Arteriogram of the coeliac trunk.

Cystic artery (10.118). Usually from the right branch of the hepatic proper, it passes behind the common hepatic and over the cystic duct to the superior aspect of the gallbladder's neck, on which it descends to divide into *superficial* and *deep* branches. The former ramifies on the inferior, the latter on the superior aspect. The cystic artery may arise from the hepatic artery itself (rarely from the gastroduodenal), crossing anterior or posterior to the bile or common hepatic duct to reach the gallbladder. Direct origin from the hepatic artery varies from its beginning to its bifurcation. An *accessory cystic artery* may arise from the common hepatic or one of its branches. The cystic artery supplies the hepatic ducts and upper part of the common bile duct (p. 1810). A comparative study of its distribution in various reptilian, avian and mammalian species included 74 injected and cleared human gallbladders (Gordon 1967). The cystic artery in man reaches the gallbladder at its neck but is not in contact with the cystic duct.

Anteriorly, two to five ascending vessels arise from the retro-duodenal branch of the gastroduodenal artery, as it crosses the anterior surface of the duct at the upper border of the duodenum. Three or four descending branches of the right hepatic and cystic arteries arise from them as these vessels pass close to the lower common hepatic duct. These ascending and descending arteries form long narrow anastomotic channels along the length of the duct, which are roughly disposed into medial and lateral trunks which some authors have described as 'three o'clock and nine o'clock' vessels. From the point of view of applied anatomy, the surgeon should dissect very carefully this area, and should keep the vessels under close endoscopic control.

Posteriorly, the 'retroportal artery' arises from the coeliac axis or superior mesenteric artery (or one of their major branches) close to the origin from the aorta, and runs upwards on the back of the portal vein. It can end in two different ways. In 20% of cases it passes up behind the bile duct to join the right hepatic artery, but in the majority it ends by joining the retroduodenal artery close to

10.117 The origin of the coeliac trunk is compressed by the median arcuate ligament of the diaphragm, formed by the right crus.

the lower end of the supraduodenal bile duct. When present, the retroportal artery plays a definite role in the blood supply of the supraduodenal duct system.

Terminal, intrahepatic branches. These display a pattern of branching relatively constant in its major details (p. 1797), which justifies a segmental description of the liver; it is the result, as in other organs, of growth and branching of an epithelial blastema, its pattern accompanied by vascular branches and nerve trunks. Arterial hepatic segmentation is described on page 1798. Consult also Woodburne (1962).

Splenic artery

The largest branch of the coeliac axis, the splenic is remarkably tortuous (**10.114- 116**). Surrounded by a splenic nerve plexus and accompanied by the straight splenic vein, it ascends to the left, behind the stomach and omental bursa, along the superior border of the pancreas; it is anterior to the left suprarenal gland and upper part of the left kidney and enters the lienorenal ligament. Nearing the spleen it divides into five or more *segmental* branches which enter its hilum (p. 1438).

Branches of the splenic artery are as follows:

Pancreatic branches (**10.115**). Numerous and small, they supply the neck, body and tail of the pancreas, leaving the splenic artery as it runs along its superior border. A *dorsal branch* (sometimes from the superior mesenteric, middle colic, hepatic or, more rarely, coeliac artery) descends posterior to the pancreas, dividing into right and left branches. The former, usually double, runs between the neck and uncinate process to form a *prepancreatic arterial arch* with a branch from the anterior superior pancreaticoduodenal; the left branch runs along the inferior border to the pancreatic tail; it anastomoses with branches (*arteria pancreatica magna* and *arteria caudae pancreatis*) from the splenic artery which supply the left part of the body and the tail.

Short gastric arteries (**10.115**). Five to seven, these arise terminally from the splenic and its final divisions or from the left gastro-epiploic artery. They pass between layers of the gastrosplenic
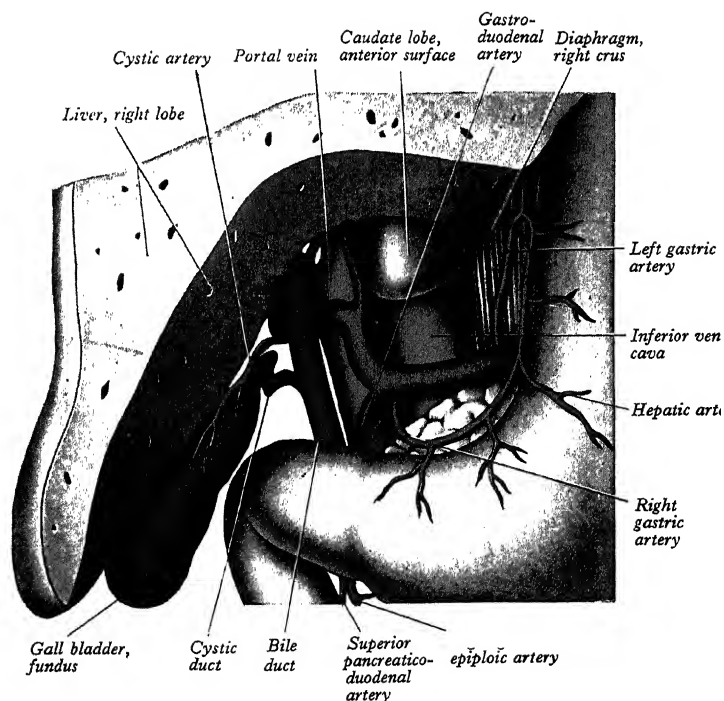
10.118 The relations of the hepatic artery, bile duct and portal vein exposed by removal of the lesser omentum and the peritoneum on the posterior abdominal wall.

1551

ligament to supply the gastric fundus, anastomosing with branches of the left gastric and gastro-epiploic arteries.

Posterior gastric artery. This arises from any part of the splenic but most commonly its middle section; it has been described by many authorities (e.g. Quain 1844) but many subsequent texts have omitted it. Suzuki et al (1978), also surveying reports on it, found it present in 38 (62.3%) of 61 adult cadavers; the incidence from 14 reports (1904–1968) varied from 12.7 to 77%, with an average of 58% in a total of 870 cadavers. They described the vessel as ascending behind the peritoneum of the omental bursa towards the gastric fundus to reach the posterior gastric wall in the gastrophrenic fold; it was usually about 2 mm in diameter.

Left gastro-epiploic artery (10.114, 115). The splenic's largest branch, it arises near the splenic hilum and runs antero-inferiorly and right, sending branches through the gastrosplenic ligament to supply the proximal third of the greater curvature; these are necessarily longer than the gastric branches of the right gastro-epiploic artery and may be 8–10 cm long. A large terminal omental branch descends to the right in the greater omentum. The main vessel curves forwards at a higher level to join the right gastro-epiploic. This loop leaves part of the greater curvature devoid of branches. At partial gastrectomy the greater omentum is divided below the right gastro-epiploic artery, cutting all omental branches; the greater omentum survives because its supply from this large omental branch of left gastro-epiploic usually escapes damage (Horton 1952). Vessels supplying the greater omentum are epiploic (omental) branches of the right and left gastro-epiploic arteries. The right, middle and left colic arteries do not supply the greater omentum; the transverse mesocolon, though usually adherent to the greater omentum, is separable from it (p. 1743).

Terminal splenic branches. These enter the hilum in the lieno-renal ligament. Their distribution is described with the spleen (p. 1439).

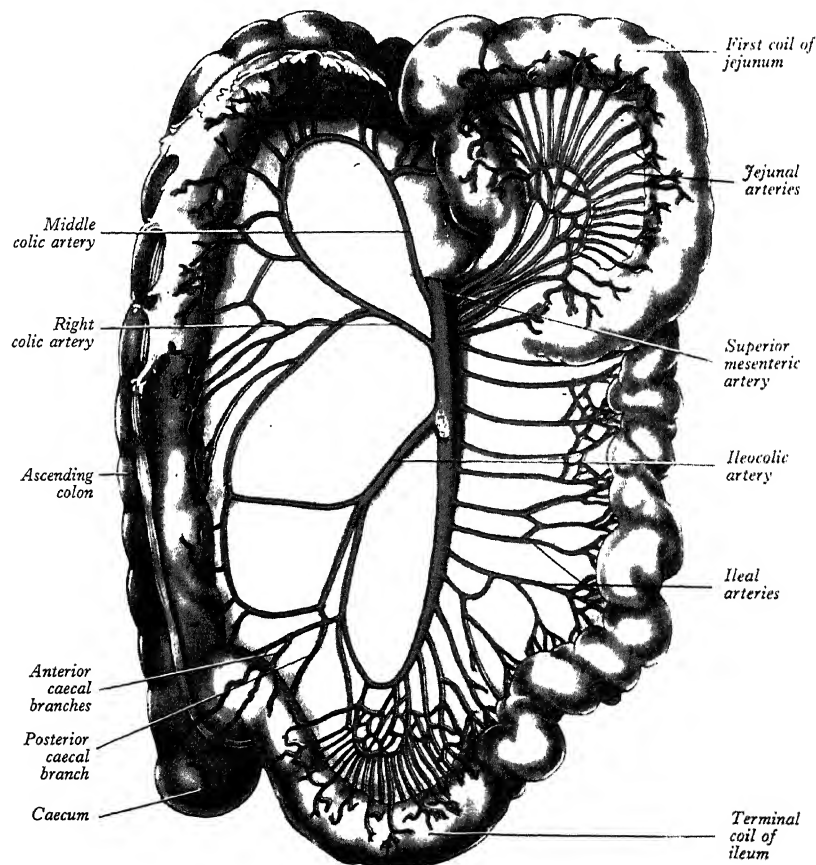## Variations of the splenic and hepatic arteries

Variations in the arrangement of these arteries and their branches are common and surgically important. They include:

- the origin of the common hepatic from the superior mesenteric or, less often, from the aorta; it usually passes behind the portal vein to enter the lesser omentum
- an *accessory left hepatic artery* most often from the left gastric artery passing right in the lesser omentum to the porta hepatis, and easily damaged during partial gastrectomy
- an *accessory right hepatic artery* most often from the superior mesenteric, usually running behind the portal vein and bile duct in the lesser omentum to the porta hepatis.

Accessory left or right hepatic arteries may also arise from the gastroduodenal or aorta. They may be combined with 'normal' branches of the hepatic artery or replace them as the sole supply to parts of the liver, being called 'aberrant replacing arteries'.

Clinical anatomy

Collateral circulation after hepatic ligature or obstruction: although blockage of the hepatic artery may lead to necrosis, this is by no means inevitable, because some two-thirds of the oxygen demands of the liver are met by the portal vein. The effect will depend on the site of the block. Occlusion of the common hepatic artery, proximal to the origin of the right gastric, allows collateral circulation to the liver through the left and right gastric, left and right gastro-epiploic, pancreaticoduodenal and gastroduodenal arteries, and so necrosis is unlikely. If, however, an obstruction of the hepatic artery proper occurs beyond the origin of the gastroduodenal artery, any collateral circulation is limited to the small inferior phrenic arteries (p. 1558).

Labels on figure:
First coil of jejunum
Jejunal arteries
Middle colic artery
Right colic artery
Superior mesenteric artery
Ileocolic artery
Ascending colon
Ileal arteries
Anterior caecal branches
Posterior caecal branch
Caecum
Terminal coil of ileum

10.119 The superior mesenteric artery and its branches. The first coil of the jejunum and the terminal coil of the ileum have been spread out to show the arrangement of their arteries.

If, of course, the portal vein has been compromised as a result of thrombosis or of surgery, then the liver is entirely dependent on the hepatic artery for its survival.

The superior mesenteric artery (10.119–121) is by far the most important of the arteries to the alimentary tract, as it supplies the whole of the small intestine from the superior part of the duodenum to the midtransverse colon, and is functionally an end artery. It leaves the front of the aorta about 1 cm below the coeliac trunk, at the level of the L1 L2 vertebral disk, and is crossed anteriorly by the splenic vein and the body of the pancreas, separated from the aorta by the left renal vein. It runs downwards and forwards, anterior to the uncinate process, and passes in front of the transverse part of the duodenum. This can sometimes be seen on a radiograph as an area of translucency, running across the duodenum, and was at one time thought to represent a sphincter (the sphincter of Ochsner) to which all manner of symptoms were attributed. Endoscopy has disproved this concept. As it descends in the root of the small bowel mesentery, the artery crosses in front of the inferior vena cava, the right ureter, and psoas major, becoming steadily narrower in its course, and eventually joins its own ileocolic branch. It is accompanied by the superior mesenteric vein and is surrounded by a plexus of nerves. A fibrous strand from the region of its last branch runs to the umbilicus, and represents a vestige of the embryonic artery which originally connected it to the yolk sac.

Inferior pancreaticoduodenal artery (10.115). It leaves the superior mesenteric, or its first jejunal branch, near the superior border of the horizontal part of the duodenum, usually dividing at once into anterior and posterior branches. The *anterior branch* passes to the right, anterior to the head of the pancreas, and ascends to anastomose with the anterior superior pancreaticoduodenal artery. The *posterior branch* ascends to the right, posterior to the head of the pancreas, which it sometimes traverses, and then anastomoses with the posterior superior pancreaticoduodenal artery. Both branches supply the pancreatic head, its uncinate process and the adjoining duodenum.

Jejunal and ileal branches (10.119, 120). These arise from the left side of the superior mesenteric; usually 12 15 are distributed to the jejunum and ileum, except in the latter's terminal part, which is supplied by the ileocolic artery. They run almost parallel in the mesentery, each dividing to unite with adjacent branches in a series of arches (10.119). Branches from these unite to form a second series and this may be repeated three or four times. In the short, upper part of the mesentery one set of arches exists but, as the mesentery increases in depth, a second, third, fourth and even fifth series appear. From the terminal arches numerous *straight* vessels supply
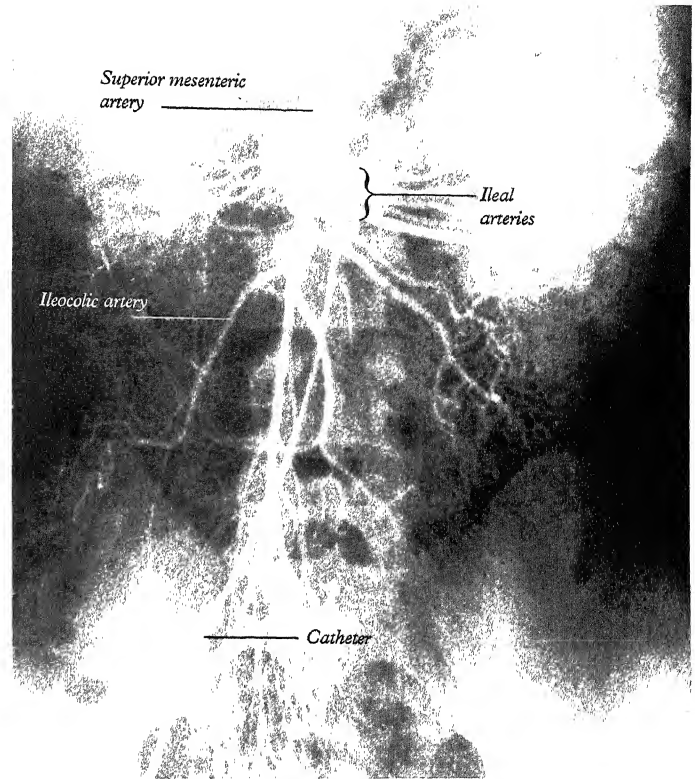
10.120 A superior mesenteric arteriogram with filling of ileal arteries (including several small branches) and of the ileocolic artery.

the intestine, distributed alternately to opposite aspects of its wall. Adjacent branches do not anastomose. Jejunal arteries are longer and fewer in number. Small twigs supply regional lymph nodes and other structures in the mesentery.

Ileocolic artery (10.119). The last branch from the right side of the superior mesenteric, it descends to the right under the parietal peritoneum to the right iliac fossa, where it divides; its *superior branch* anastomoses with the right colic, the inferior with the end of the superior mesenteric. The ileocolic artery crosses anterior to the right ureter, testicular or ovarian vessels and psoas major. Its *inferior branch* approaches the superior border of the ileocolic junction and branches as follows (10.119, 122):
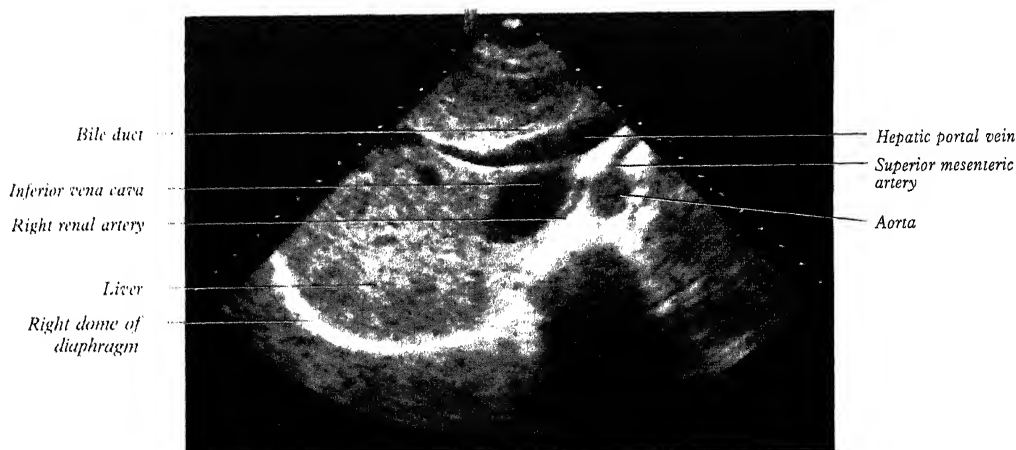
10.121 Ultrasonogram through the origin of the superior mesenteric artery. (Provided by Shaun Gallagher, Guy's Hospital; photography by Sarah Smith.)
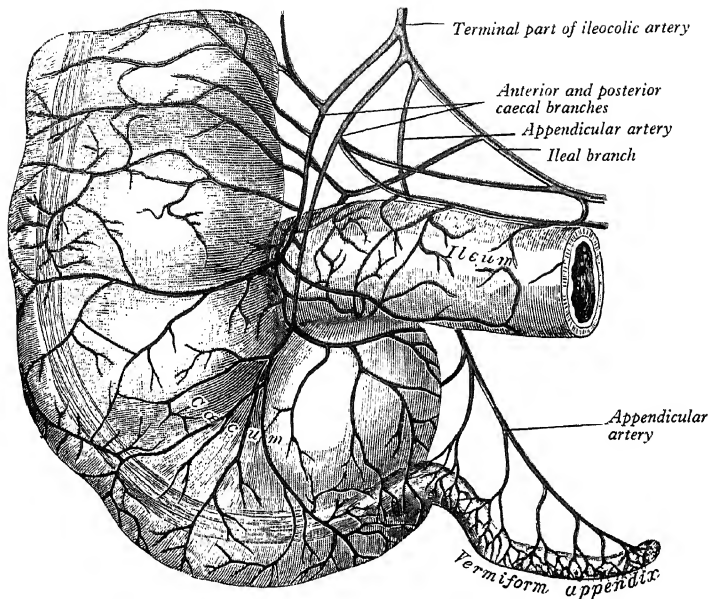
10.122 The arteries of the caecum and vermiform appendix.

close to and then in the edge of the mesoappendix, its terminal part being in actual contact with the appendix

• an *ileal* branch ascending to the left on the lower ileum, supplying it and anastomosing with a terminal twig of the superior mesenteric artery.

**Right colic artery** (10.119). This is a small vessel and it may be absent. It arises near the middle of the superior mesenteric, or in common with the ileocolic and passes to the right behind the parietal peritoneum and anterior to the right ovarian or testicular artery and vein, right ureter and psoas major, towards the ascending colon. Sometimes it is higher and crosses the descending duodenum and right inferior renal pole. Near the colon it divides into a descending branch, which anastomoses with the ileocolic, and an ascending branch anastomosing with the middle colic. These form arches, from which vessels are distributed to the ascending colon, supplying its upper two-thirds and the right colic flexure.

Middle colic artery (10.119). It leaves the superior mesenteric just inferior to the pancreas; descending in the transverse mesocolon it divides into a right and left branch; the former anastomoses with the right colic artery, the latter with the left, a branch of *inferior* mesenteric. Arches thus formed are 3 or 4 cm from the transverse colon, which they supply.

Variations

The superior mesenteric artery may be the source of the common hepatic, gastroduodenal, accessory right hepatic, accessory pancreatic or splenic arteries. It may arise from a common coeliaco-mesenteric trunk (Mangoushi 1975).

ascending (*colic*) passing up on the ascending colon
anterior and *posterior caecal*
an *appendicular artery*, descending behind the terminal ileum to enter the mesoappendix; after giving off a recurrent branch anastomosing with one from the posterior caecal artery, it runs

The inferior mesenteric artery (10.123–127) supplies the left third of the transverse colon, all the descending colon, sigmoid colon and most of the rectum. It is smaller than the superior mesenteric, arising
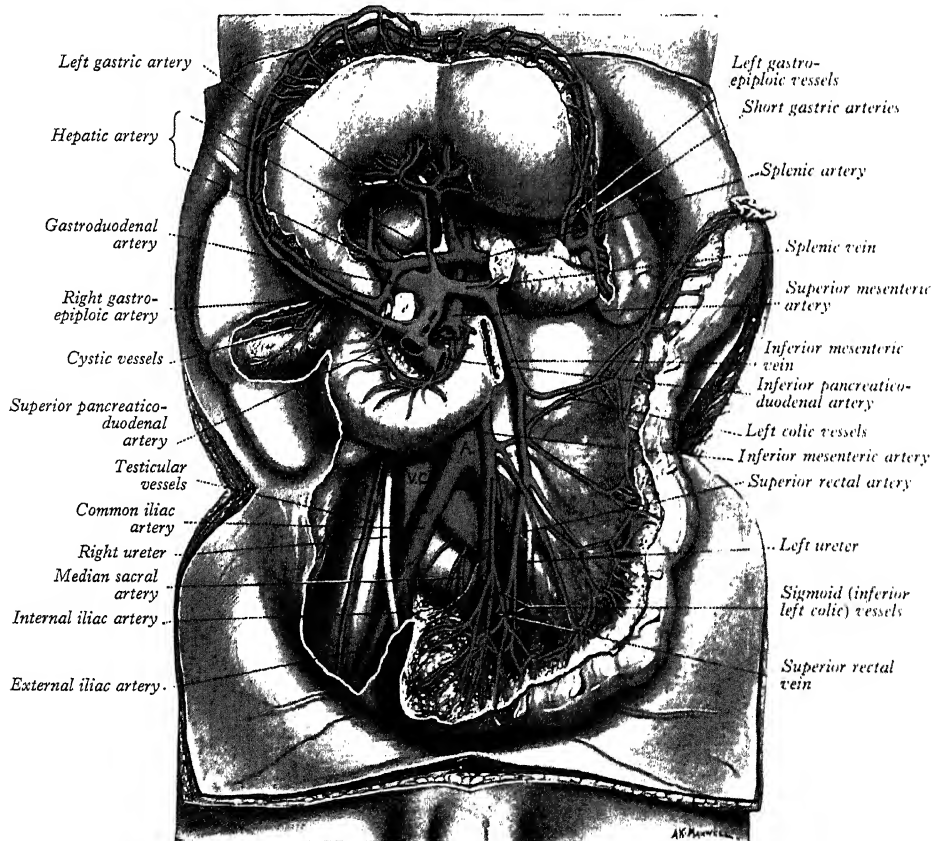
10.123 The inferior mesenteric vessels and their branches (male subject). Note the stomach has been turned upwards and the whole of the jejunum and ileum, the caecum, ascending colon and transverse colon have been removed, together with part of the pancreas.

10.125 Sigmoid colon and rectum, showing the distribution of the branches of the inferior mesenteric artery and their anastomoses.

10.124 Inferior mesenteric arteriogram. When the superior mesenteric artery is blocked, the marginal artery to the colon enlarges and the inferior mesenteric artery then becomes the blood supply to the midgut.

3 or 4 cm above the aortic bifurcation, posterior to the horizontal part of the duodenum. It descends behind the peritoneum, at first anterior to the aorta, then on its left, crosses the left common iliac artery medial to the left ureter and then enters and continues in the sigmoid mesocolon into the lesser pelvis as the *superior rectal artery*. Distally the inferior mesenteric vein is lateral. The artery has left colic, sigmoid and superior rectal branches.

Left colic artery (10.123–127). It ascends subperitoneally to the left, anterior to the psoas major, and divides into ascending and descending branches. The trunk and its branches cross the left ureter and ovarian or testicular ves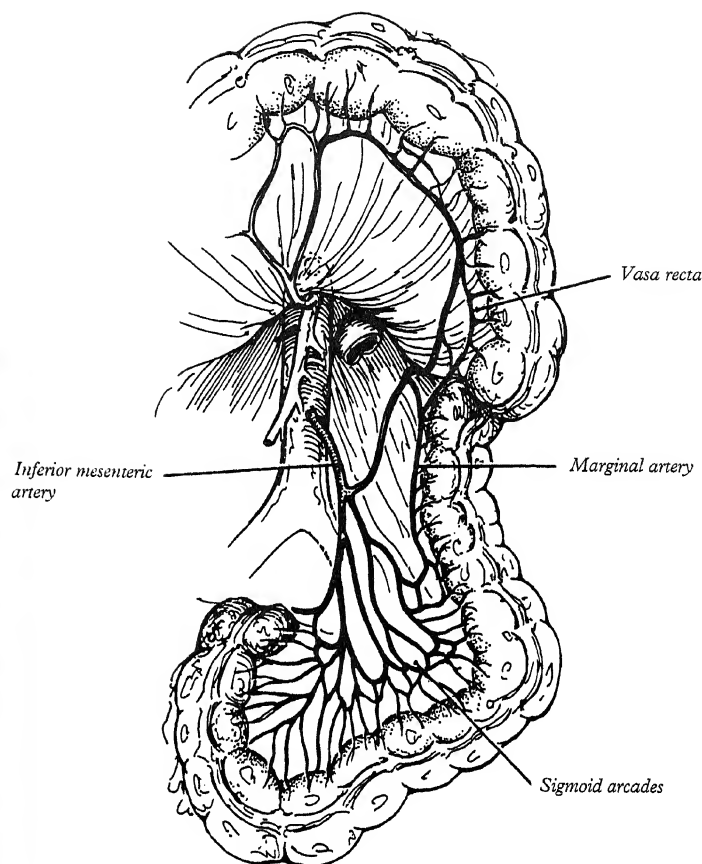sels. The ascending branch passes anterior to the left kidney into the transverse mesocolon, where it anastomoses with the middle colic artery; the descending branch anastomoses with the highest sigmoid artery. From arches thus formed, branches supply the left half of the transverse and the descending colon. Territories of supply by middle and left colic arteries show reciprocal variation; the left branch of the middle colic may take over the supply of the splenic flexure (in 19 of 100 cadavers, according to Sierociński 1975).

Sigmoid (inferior left colic) arteries (10.123–127). Two or three in number, they descend obliquely to the left under the peritoneum anterior to the left psoas major, ureter and testicular or ovarian vessels. Branches supply the lower descending colon and sigmoid

colon, anastomosing above with the left colic artery, below with the superior rectal artery.

Superior rectal artery (10.123–126). A continuation of the inferior mesenteric, it descends into the pelvis in the sigmoid mesocolon, crossing the left common iliac vessels. It divides, near the third sacral vertebra, into two branches descending one on each side of the rectum; about halfway they divide into smaller branches, which pierce the muscular rectal wall to descend vertically, at submucosal level, to the sphincter ani internus; here, by mutual anastomoses, they form loops around the lower rectum, communicating with the middle rectal artery, a branch of the internal iliac, and with the inferior rectal from the internal pudendal (p. 1561).

Marginal artery of the colon. This is formed by the union of the three main colonic branches described above, which arise from the right side of the superior mesenteric artery and then continue around the splenic flexure to join the upward running left colic branch of the inferior mesenteric artery. This is an important vessel from the clinical point of view, because in the event of an occlusion of the two upper vessels (the coeliac trunk and the superior mesenteric artery) it represents the only surviving route of supply to the alimentary tract, flow proceeding retrograde from the inferior mesenteric artery to the superior mesenteric artery (see **10.124–126**). The arrangement of vessels along the right colon is fairly constant, there being one marginal artery giving off *vasa recta* and *vasa brevia*, which occasionally communicate, although the anastomoses are less well developed than they are in the small bowel. It is at the point of junction of the superior and inferior mesenteric system (at the splenic flexure) that confusion and variability occur.

Relations

The inferior mesenteric artery divides into two or three branches, the uppermost of which (the left colic) almost always reaches the
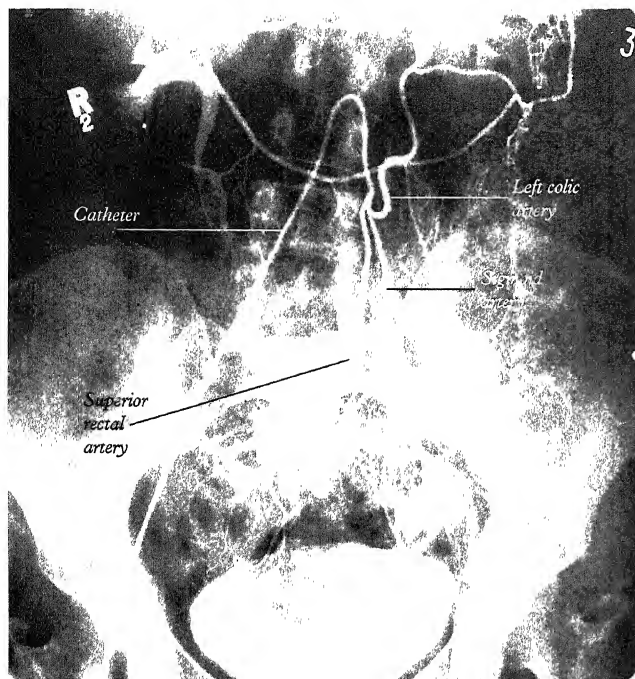
10.126 Arteriogram of the inferior mesenteric.

splenic flexure. Here it bifurcates, the slender outer branch joining the left branch of the middle colic from the marginal artery (of Drummond) of the colon, the inner (larger) branch running back into the trunk of the middle colic artery to form an additional arcade, the *arc of Riolan*. The outer anastomosis is here often small or incomplete, so that the continuity of the marginal artery is broken. If the arc of Riolan is not well developed, then there exists a critical area of anastomotic supply, so that impairment of flow either in the superior mesenteric artery or the inferior mesenteric artery will not be compensated, and ischaemic damage may ensue. This explains the relative frequency of ischaemic lesions in the region of the splenic flexure. It used to be taught that there was a critical point (of Sudek) between the last sigmoid branch and the first rectal branch of the superior haemorrhoidal artery, but that is now known not to be the case. The arterial anastomosis here is well-developed (see **10.127**) and if a critical point exists at all then it is at the splenic flexure, as already described.

Clinical anatomy

When the superior mesenteric artery is completely occluded, then the marginal artery to the colon may become enormously dilated (see **10.124**) as it is required to supply the whole of the midgut loop. Alternatively, occlusion of the aorta or common iliac arteries may result in a similar dilatation of the marginal artery, which then becomes an important source of collateral supply to the legs.

ANTEROLATERAL VISCERAL ARTERIES

Middle suprarenal arteries

These two small vessels arise laterally from each side of the aorta, level with the superior mesenteric, ascending slightly over the crura

10.127 An inferior mesenteric arteriogram showing details of the intramural colonic circulation and the occurrence of good anastomotic connections around Sudek's point.

of the diaphragm to the suprarenal glands, where each anastomoses with the suprarenal branches of the phrenic and renal arteries. The right passes behind the inferior vena cava and near the right coeliac ganglion; the left is related to the left coeliac ganglion, splenic artery and superior border of the pancreas.

Renal arteries

These two large vessels branch laterally from the aorta just below the inferior mesenteric; both cross the corresponding crus at right angles to the aorta (**10.**112, 113, 128). The **right** is longer and often higher, passing posterior to the inferior vena cava, right renal vein, head of the pancreas and descending part of the duodenum. The **left** is a little lower; it passes behind the left renal vein, the body of the pancreas and splenic vein and may be crossed anteriorly by the inferior mesenteric vein. Nearing its renal hilum, each divides into four or five branches, most between the renal vein and ureteric pelvis, the vein being anterior, the pelvis posterior, but one or more usually behind the pelvis. Each renal artery supplies small *inferior suprarenal branches* (p. 204) and also the ureter, surrounding cellular tissue and muscles. The distribution of the renal arteries is described on page 1826.

Surface anatomy. The renal arteries can be projected as broad lines running laterally for 4 cm from the aorta (**10.**112) just inferior to the transpyloric plane; the left inclines across the plane.

Variations. One or two *accessory renal arteries* frequently occur, especially on the left, usually from the aorta above or below the main artery, the former slightly more often. They usually enter above or below the renal hilum; if below, the vessel crosses anterior to the ureter and, on the right, usually also anterior to the inferior vena cava.
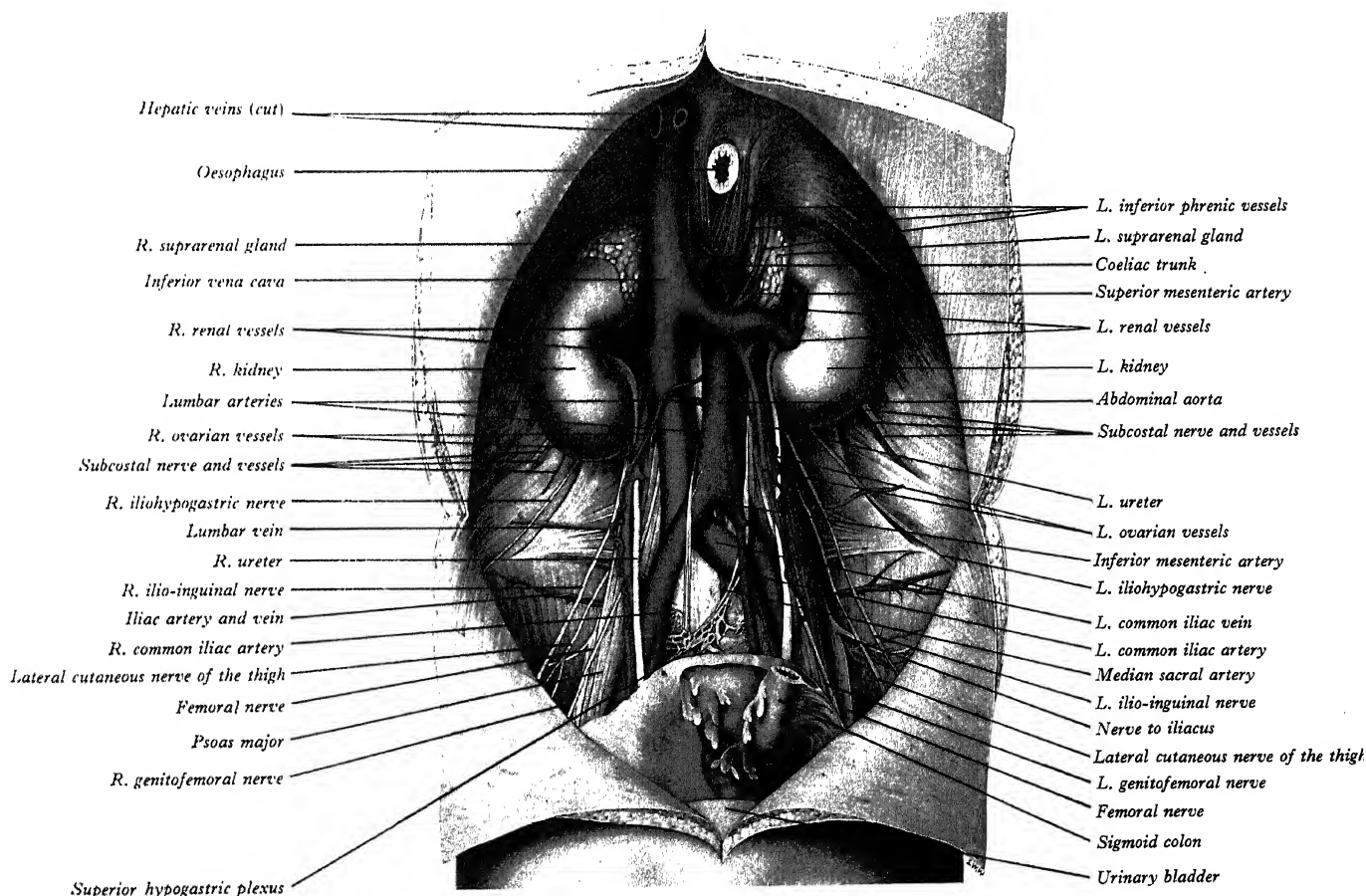
Testicular arteries

These two long, slender vessels arise anteriorly from the aorta a little inferior to the renal arteries (**10.**112, 113, 128). Each passes inferolaterally under the parietal peritoneum on the psoas major; the *right* lies anterior to the inferior vena cava and posterior to the horizontal part of the duodenum, right colic and ileocolic arteries, root of the mesentery and terminal ileum; the *left* testicular artery lies posterior to the inferior mesenteric vein, left colic artery and lower part of the descending colon. Each crosses anterior to the genitofemoral nerve, ureter and the lower part of the external iliac artery, passing to the deep inguinal ring to enter the spermatic cord with other constituents, via which the vessel traverses the inguinal canal to the scrotum. At the posterosuperior aspect of the testis it divides into two branches on its medial and lateral surfaces, which pass through its tunica albuginea to ramify in the tunica vasculosa. Terminal branches enter the testis over its surface. Some pass into the mediastinum testis and loop back before reaching their distribution (Harrison & Barclay 1948). In the abdomen the testicular artery supplies perirenal fat, ureter and iliac lymph nodes; in the inguinal canal it supplies the cremaster.

Sometimes the right testicular artery passes **posterior** to the inferior vena cava. Both arteries represent persistent lateral splanchnic aortic branches (p. 318) which enter the mesonephros and cross ventral to the supracardinal but dorsal to the subcardinal vein. Normally the lateral splanchnic artery which persists as the *right* testicular passes **caudal** to the suprasubcardinal anastomosis forming part of the inferior vena cava (p. 318). When it passes **cranial** to this, the right testicular artery is behind the inferior vena cava.

Clinical anatomy. The testicular artery is not the sole supply to the testis, which also receives some blood from the cremasteric branch of the inferior epigastric artery (see p. 1563). Thus interference with the testicular artery high in the abdomen usually leaves the testis unharmed, whereas interruption in the region of the spermatic cord involves both sets of vessels and leads to infarction.

Labels on the dissection image, left side (top to bottom):
Hepatic veins (cut)
Oesophagus
R. suprarenal gland
Inferior vena cava
R. renal vessels
R. kidney
Lumbar arteries
R. ovarian vessels
Subcostal nerve and vessels
R. iliohypogastric nerve
Lumbar vein
R. ureter
R. ilio-inguinal nerve
Iliac artery and vein
R. common iliac artery
Lateral cutaneous nerve of the thigh
Femoral nerve
Psoas major
R. genitofemoral nerve
Superior hypogastric plexus

Labels on the dissection image, right side (top to bottom):
L. inferior phrenic vessels
L. suprarenal gland
Coeliac trunk
Superior mesenteric artery
L. renal vessels
L. kidney
Abdominal aorta
Subcostal nerve and vessels
L. ureter
L. ovarian vessels
Inferior mesenteric artery
L. iliohypogastric nerve
L. common iliac vein
L. common iliac artery
Median sacral artery
L. ilio-inguinal nerve
Nerve to iliacus
Lateral cutaneous nerve of the thigh
L. genitofemoral nerve
Femoral nerve
Sigmoid colon
Urinary bladder

10.128 Dissection to show the relations of structures on the posterior abdominal wall (female subject).

Ovarian arteries

These correspond to the testicular arteries but enter the pelvis to supply the ovaries (10.132). Initially they resemble the testicular arteries but at the brim of the lesser pelvis each crosses the lower external iliac artery and vein to enter the true pelvic cavity, turning medially in the ovarian suspensory ligament to continue into the uterine broad ligament, below the uterine tube. At ovarian level it passes back in the mesovarium and divides into branches to the ovary. Small branches supply the ureter and uterine tube and one passes to the side of the uterus to unite with the uterine artery. Others accompany the round ligament through the inguinal canal to the skin of the labium majus and the inguinal region.

Early in intrauterine life, when testes or ovaries flank the vertebral column inferior to the kidneys, the testicular and ovarian arteries are relatively short; but with descent of the gonads into the pelvis and beyond, they gradually lengthen.

(Inferior) phrenic arteries

These two small vessels help to supply the diaphragm (10.112, 113, 128), They may arise separately from the aorta, just above its coeliac trunk, by a common aortic stem or from the coeliac trunk; sometimes one is from the aorta, the other from a renal artery. Each artery ascends laterally anterior to a crus of the diaphragm, near the medial border of the suprarenal gland. The **left** passes behind the oesophagus and forwards on the left side of its diaphragmatic opening. The **right** phrenic passes posterior to the inferior vena cava then along the right of its opening. Near the posterior border of the diaphragm's central tendon each divides into medial and lateral branches. The medial curves forwards to anastomose with its fellow in front of the central tendon and with the musculophrenic and pericardiacophrenic arteries; the lateral approaches the thoracic wall, anastomosing with the lower posterior intercostal and musculophrenic arteries. The lateral branch of the right artery supplies the inferior vena cava while the left sends ascending branches to the oesophagus. Each has two or three small *superior suprarenal branches*. The liver (p. 1556) and spleen also receive small branches from the phrenic arteries.

Lumbar arteries

These are in series with the posterior intercostal arteries (10.128). Usually four on each side, they arise posterolaterally from the aorta, opposite the lumbar vertebrae. A fifth, smaller pair occasionally arise from the median sacral artery but lumbar branches of the iliolumbar arteries usually take their place. The lumbar arteries run posterolaterally on the four upper lumbar vertebral bodies, behind the sympathetic trunks, to intervals between the lumbar transverse processes and continue into the abdominal wall. The right arteries pass posterior to the inferior vena cava; the upper two right and first left are also posterior to the corresponding crus. Arteries of both sides pass under tendinous arches (which span the lateral concavities of the vertebral bodies, p. 870) for attachment of psoas major, proceeding posterior to the muscle and the lumbar plexus. They then cross the quadratus lumborum, the upper three posterior, the last usually anterior to it. At its lateral border they pierce the posterior aponeurosis of the transversus abdominis, advancing between it and the internal oblique. They anastomose with one another and the lower posterior intercostal, subcostal, iliolumbar, deep circumflex iliac and inferior epigastric arteries.

Branches. Each lumbar artery has a *dorsal branch* passing back between the adjacent transverse processes to supply the dorsal muscles, joints and skin; this also has a spinal branch entering the vertebral canal to supply its contents and adjacent vertebra, anastomosing with the arteries above and below it and across the midline. The *spinal branch* of the first lumbar supplies the terminal spinal cord itself; the remainder supply the cauda equina, meninges and vertebral canal. Branches of the lumbar arteries and their dorsal branches supply the adjacent muscles, fasciae, bones, red marrow, ligaments and joints (symphyses, syndesmoses and synovial joints).

Median sacral artery

This small posterior branch leaves the aorta a little above its bifurcation (10.112, 113, 128). It descends in the midline, anterior to the fourth and fifth lumbar vertebrae, sacrum and coccyx, ending in the coccygeal body. At fifth lumbar level it is crossed by the left

common iliac vein and often gives off a small lumbar artery (*arteria lumbalis ima*), minute branches of which reach the rectum. Anterior to the last lumbar vertebra the median sacral anastomoses with a lumbar branch of the iliolumbar; anterior to the sacrum it anastomoses with the lateral sacral arteries and sends branches into the anterior sacral foramina.

ARTERIES

The abdominal aorta bifurcates, anterolateral to the **left** side of the **fourth** lumbar vertebral body, into the right and left common iliac arteries (10.112, 113, 128, 129). These diverge as they descend to divide near the level of the lumbosacral intervertebral disc (between the last lumbar and first sacral vertebrae) into external and internal iliac arteries; the former supplies most of the lower limb, the latter the pelvic viscera and walls, perineum and gluteal region. The division of the common iliac is anterior to its sacro-iliac joint.

A collateral circulation may be established, in young adults, after ligature of the common iliac artery; when arterial walls degenerate in older patients it is unlikely to supply the leg adequately.

Right common iliac artery

This is about 5 cm long and passes obliquely across part of the fourth and the fifth lumbar vertebral body (10.112, 113, 128, 129). Anteriorly, it is crossed by the sympathetic rami to the pelvic plexus and, at its division, by the ureter; it is covered by the parietal peritoneum, which separates it from the coils of the small intestine. Posteriorly, it is separated from the fourth and fifth lumbar vertebral bodies and their intervening disc by the sympathetic trunk, the terminal parts of the common iliac veins and the commencement of the inferior vena cava; the obturator nerve, lumbosacral trunk and iliolumbar artery are also posterior, traversing fatty tissue between
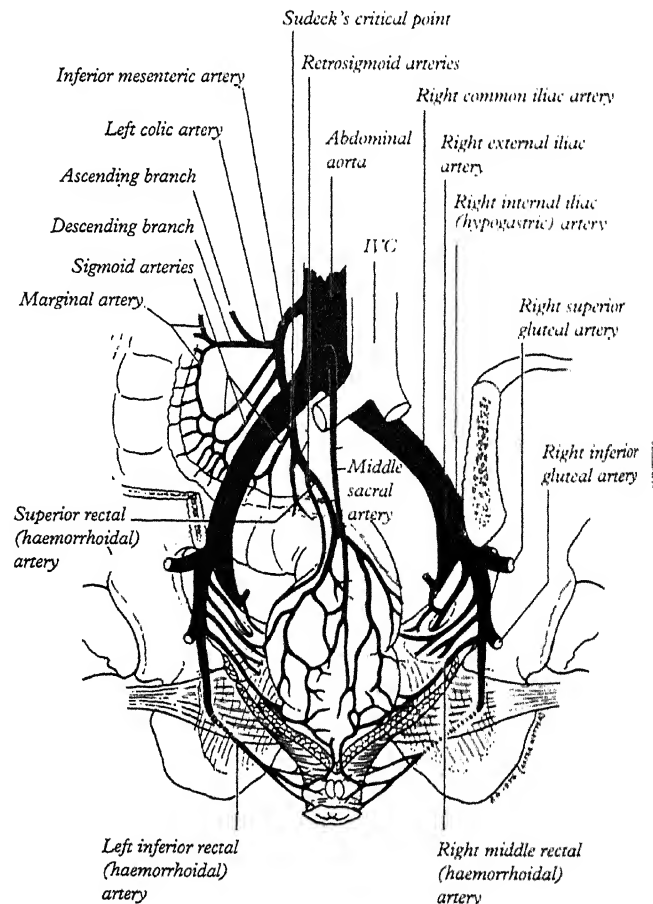
10.129 Schematic representation of the main vessels in the pelvic cavity, seen from the back (after Netter).

the fifth lumbar vertebra and the psoas major. **Lateral** to its upper part are the inferior vena cava and the right common iliac vein to which it has a surgically important relationship (see above); lateral to its lower part is the right psoas major; **medial** to its upper part is the left common iliac vein.

Left common iliac artery

The artery is about 4 cm long (**10.**112, 113, 128, 129). **Anterior** are the peritoneum, ileum, the sympathetic rami to the pelvic plexus, the superior rectal artery and, at its terminal bifurcation, the ureter. Posterior are the sympathetic trunk, fourth and fifth lumbar vertebral bodies and intervening disc; the obturator nerve, lumbosacral trunk and iliolumbar artery are more posterior (i.e. deeply situated). The left common iliac vein is partly **medial**, partly **posterior** to the artery; **lateral** and closely related is the left psoas major.

Surface anatomy. The vessel corresponds to the superior third of a broad line from the aortic bifurcation (p. 1547) to a point midway between the anterior superior iliac spine and the pubic symphysis. The *external iliac artery* corresponds to the inferior two-thirds of this line, which is laterally slightly convex.

Branches. In addition to the terminal branches, each common iliac artery gives small branches to the peritoneum, psoas major, ureter, adjacent nerves and surrounding areolar tissue; occasionally it has the iliolumbar and accessory renal arteries as branches.

Each internal iliac artery (**10.**130, 131), about 4 cm long, begins at the common iliac bifurcation, level with the lumbosacral intervertebral disc and anterior to the sacro-iliac joint; it descends posteriorly to the superior margin of the greater sciatic foramen, dividing here into: an *anterior trunk*, which continues in the same line towards the ischial spine; and a *posterior trunk*, passing back to the foramen (Braithwaite 1952). **Anterior** are the ureter and, in females, the ovary and fimbriated end of the uterine tube; **posterior** are the internal iliac vein, lumbosacral trunk and sacro-iliac joint; **lateral** is the external iliac vein, between the artery and the psoas major and inferior to this the obturator nerve; **medial** is the parietal

peritoneum, separating it from the terminal ileum on the right and the sigmoid colon on the left, and tributaries of the internal iliac vein.

In the fetus the internal iliac artery is twice the size of the external and is the direct continuation of the common iliac. It ascends on the anterior abdominal wall to the umbilicus, converging on its fellow. Having traversed the opening, the two arteries, now umbilical, enter the umbilical cord, coil round the umbilical vein and ultimately ramify in the placenta. At birth, when placental circulation ceases, only the pelvic segment remains patent as the internal iliac artery and part of the superior vesical, the remainder becoming a fibrous *medial umbilical ligament* raising the peritoneal *medial umbilical fold* from the pelvis to the umbilicus. In males, the patent part usually gives off an artery to the ductus deferens (see below).

BRANCHES OF ANTERIOR TRUNK OF INTERNAL ILIAC ARTERY

Superior vesical artery (**10.**130, 131). This supplies many branches to the vesical fundus (Braithwaite 1951); from one the *artery to the ductus deferens* occasionally starts and accompanies the ductus to the testis, anastomosing with the testicular artery. Others supply the ureter. The beginning of the superior vesical artery is the proximal, patent section of the fetal umbilical artery (see above).

Inferior vesical artery (**10.**130, 131). Often arising with the middle rectal, it supplies the vesical fundus, prostate, seminal vesicles and lower ureter. Prostatic branches communicate across the midline. The inferior vesical may sometimes provide the artery to the ductus deferens.

Middle rectal artery (**10.**125, 130). It usually arises with the inferior vesical. It vascularizes muscular tissue in the lower rectum, anastomosing with the superior and inferior rectal arteries. It supplies the seminal vesicles and prostate by branches which join those of the inferior vesical.

Uterine artery (**10.**132). This runs medially on the levator ani to the cervix uteri; about 2 cm from this it crosses above the *ureter*, to which it supplies a small branch, and above the *lateral vaginal fornix*. It ascends tortuously lateral to the uterus in its broad ligament to the junction of the uterine tube and uterus, turning laterally towards
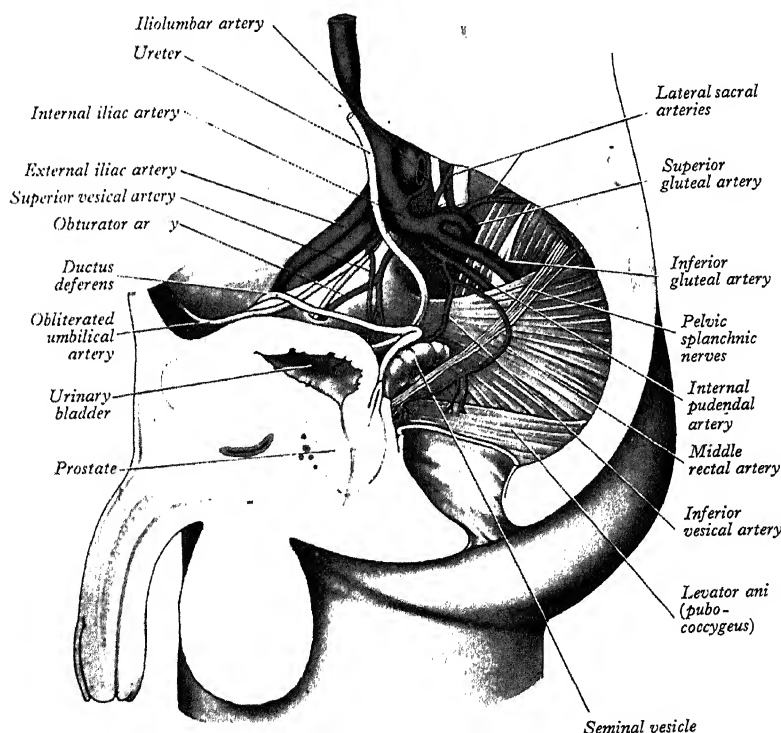
10.130 The arteries of the male pelvis (right side). The internal iliac vein and its tributaries have been removed; the rectum has been divided just above the anal canal and its upper part has been taken away.

Auricular surface of sacrum · Rectum · Internal iliac artery · Peritoneum · Psoas major · Superior gluteal artery · Ureter · Part of sacral plexus · External iliac vessels · Piriformis · Obturator nerve · Inferior gluteal artery · Ductus deferens · Obliterated umbilical artery · Urinary bladder · Gluteus maximus · Spine of ischium · Sacrotuberous ligament · Internal pudendal artery · Pectineus · Levator ani · Perineal nerve · Crus penis · Superficial fascia, membranous layer · Dorsal nerve of penis · Inferior fascia of urogenital diaphragm

10.131 Structures of the male pelvic contents from the left side. Most of the left innominate bone has been removed together with the obturator internus. The sciatic nerve has been cut away close to its origin from the sacral plexus. All the vessels and nerves exposed are those of the left side. Note the superior vesical, obturator, inferior vesical and middle rectal arteries which are, for technical reasons, unlabelled.

the ovarian hilum, and ends by joining the ovarian artery. It supplies the cervix uteri and branches descend on the vagina, anastomosing with branches of the vaginal arteries to form two median longitudinal vessels, the *azygos arteries of the vagina*; one descends anterior, the other posterior, to the vagina. The uterine artery supplies the body of the uterus, uterine tube and round ligament of the uterus. Terminal branches in the uterine muscle are tortuous *helicine arteries*.

Vaginal artery. Often double or triple, it corresponds to the inferior vesical in males; it descends on the vagina, supplying mucous membrane, and sends branches to the vestibular bulb, vesical fundus and the adjacent part of the rectum. It assists in forming the azygos arteries of the vagina (see above).

Obturator artery (10.130). It inclines antero-inferiorly on the lateral pelvic wall to the upper part of the obturator foramen. Leaving the pelvic cavity by the obturator canal, it divides into anterior and posterior branches. In the pelvis it is related laterally to the obturator fascia, separating it from the obturator internus; it is crossed medially by the ureter and the ductus deferens, separating it from the parietal peritoneum. In the nullipara the ovary is medial. The obturator nerve is above, the vein below.

Branches. In the pelvis, the obturator artery provides:

* *iliac branches* to the iliac fossa, supplying the bone and iliacus and anastomosing with the iliolumbar artery

* a *vesical branch* passing medially to the bladder, sometimes replacing the inferior vesical branch of the internal iliac
* a *pubic branch* just before it leaves the pelvis, which ascends over the pubis to anastomose with its fellow and the pubic branch of the inferior epigastric.

Outside the pelvis its anterior and posterior terminal branches encircle the foramen between the obturator externus and the obturator membrane. The *anterior branch* curves forwards on the membrane and then down along its anterior margin, supplying branches to the obturator externus, pectineus, femoral adductors and gracilis and anastomosing with the posterior branch and the medial circumflex femoral artery. The *posterior branch* follows the foramen's posterior margin and turns forwards on the ischial branch to anastomose with the anterior. It supplies the muscles attached to the ischial tuberosity and anastomoses with the inferior gluteal. An *acetabular branch* enters the hip joint at the acetabular notch, ramifies in the fat of the acetabular fossa and sends a branch along the ligament of the femoral head.

Variations. In 20–30% of subjects the obturator artery is replaced by an enlarged pubic branch of the inferior epigastric (p. 1563); this descends almost vertically to the obturator foramen. Such an abnormal obturator artery is usually near the external iliac vein, lateral to the femoral ring, and is then safe in herniotomy. Sometimes
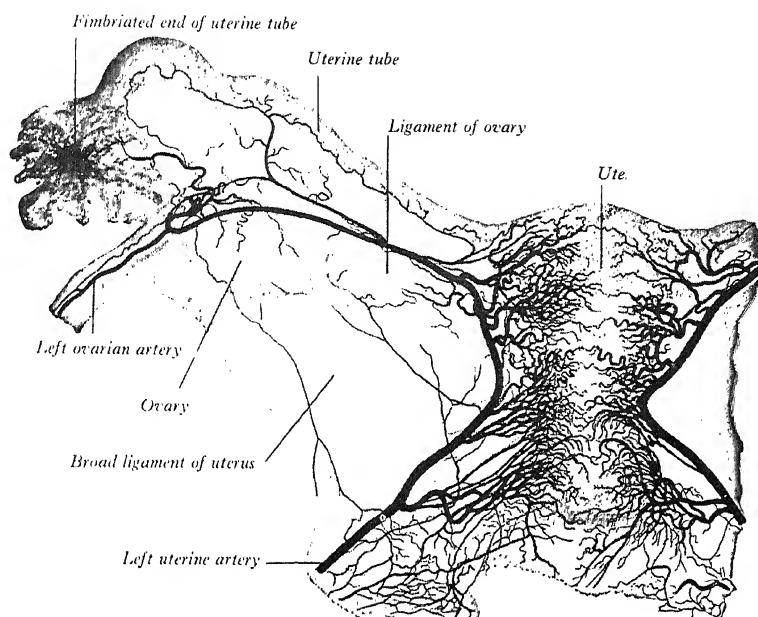
10.132 The left uterine and ovarian arteries of a nullipara of 17½ years: posterior aspect. (From a preparation by Hamilton Drummond.)

it curves along the edge of the lacunar part of the inguinal ligament, partly encircling the neck of a hernial sac, and may be inadvertently cut during enlargement of the femoral ring in reducing a femoral hernia.

Internal pudendal artery in the male (10.130, 131, 133, 134)

The artery descends laterally to the inferior rim of the greater sciatic foramen, where it leaves the pelvis between piriformis and coccygeus and enters the *gluteal region*; then curving around the dorsum of the ischial spine to enter the perineum by the lesser sciatic foramen, it traverses the pudendal canal in the lateral wall of the *ischiorectal fossa*, medial to the obturator internus, about 4 cm above the ischial tuberosity's lower limit. Approaching the margin of the ischial branch, it proceeds above or below the inferior fascia of the urogenital diaphragm along the medial margin of the inferior pubic ramus and ends behind the inferior pubic ligament, dividing into the *deep* and *dorsal arteries of the penis*. It may descend through the inferior fascia before its division. (The internal pudendal distal to its perineal branch has been named *artery of the penis*, appropriately in view of its distribution; see below.)

Relations. In the pelvis the internal pudendal artery crosses anterior to the piriformis, sacral plexus and inferior gluteal artery. Behind the ischial spine it is covered by the gluteus maximus, with the pudendal nerve medial and the nerve to obturator internus lateral. In the pudendal canal (p. 832) it travels at first with companion veins and the pudendal nerve; beyond this the dorsal nerve of the penis is above, the perineal nerve below.

Muscular branches (10.133, 134). These leave the artery in the pelvis and gluteal region to supply the adjacent muscles and nerves.

Inferior rectal artery. This arises above the ischial tuberosity. Escaping from the pudendal canal (p. 832), it divides into two or three branches crossing the ischiorectal fossa medially to supply the anal skin and musculature. Small branches skirt the lower edge of the gluteus maximus to supply the gluteal skin. The inferior rectal anastomoses with its fellow, and with the superior, middle rectal and perineal arteries.

Perineal artery (10.133). It leaves the internal pudendal near the anterior end of its canal, turns down through the inferior fascia of the urogenital diaphragm (p. 834) and approaches the scrotum in the superficial perineal region, between the bulbospongiosus and ischiocavernosus. Beyond the diaphragm, and near its base, a small *transverse branch* passes medially inferior to the superficial transverse perineal muscle to anastomose with its fellow and the posterior

scrotal and inferior rectal arteries, supplying tissues between the anus and the penile bulb. The posterior *scrotal arteries*, distributed to the scrotal skin and dartos muscle, are usually terminals of the perineal but may also arise from its transverse branch; they also supply the perineal muscles.

Artery of the bulb of the penis. Short but wide, it runs medially through the deep transverse perineal muscle and inferior urogenital fascia to the penile bulb. Penetrating this, it supplies the posterior part of the corpus spongiosum and the bulbo-urethral gland.

Urethral artery. This traverses the urogenital diaphragm's inferior fascia and enters the corpus spongiosum, reaching the glans penis. It supplies the urethra and erectile tissue around it.

Deep artery of the penis. A terminal branch of the internal
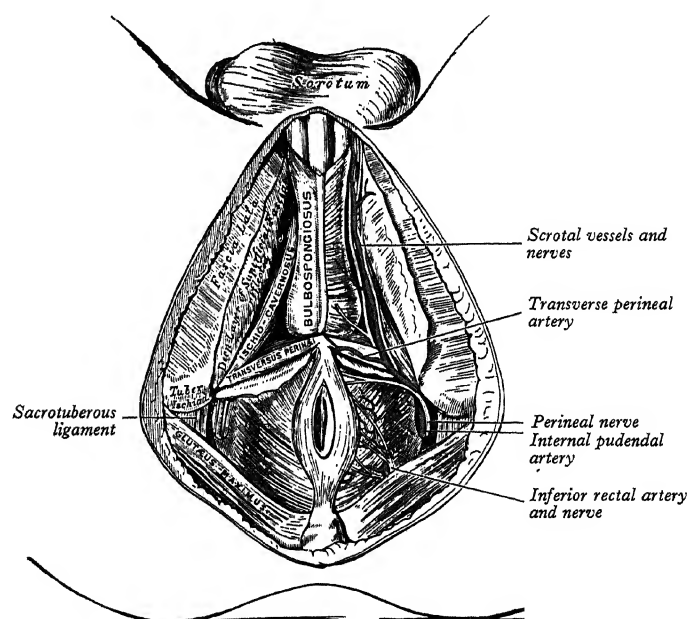
10.133 The superficial branches of the internal pudendal artery, in the male.
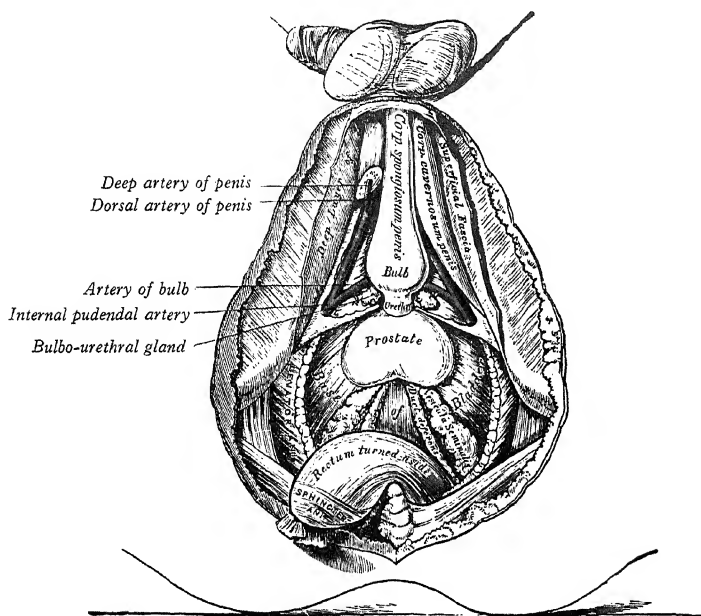
10.134 The deeper branches of the internal pudendal artery, in the male.

Deep artery of penis
Dorsal artery of penis
Artery of bulb
Internal pudendal artery
Bulbo-urethral gland

pudendal, it passes through the inferior fascia of the urogenital diaphragm to enter the crus penis. It traverses the corpus cavernosum and supplies its erectile tissue.

Dorsal artery of the penis. The other terminal branch of the internal pudendal, it leaves the inferior aspect of the urogenital diaphragm, **ascends** between the crus penis and pubic symphysis, and traverses the suspensory ligament of the penis to run along its dorsum to the glans, where it forks into branches to the glans and prepuce. In the penis it lies between its dorsal nerve and deep dorsal vein, the latter being most medial. It supplies penile skin and the fibrous sheath of the corpus cavernosum, anastomosing through the sheath with the deep penile artery.

Inferior gluteal artery

The larger terminal branch of the anterior internal iliac trunk, it chiefly supplies the buttock and thigh. It descends anterior to the sacral plexus and piriformis, posterior to the internal pudendal artery (**10.129, 135**). Passing between the first and second or second and third sacral anterior spinal nerve rami, then between the piriformis and coccygeus, it traverses the lower part of the greater sciatic foramen to reach the gluteal region. Descending between the greater trochanter and ischial tuberosity with the sciatic and posterior femoral cutaneous nerves, deep to the gluteus maximus, it continues down the thigh, supplying the skin and anastomosing with branches of the perforating arteries. The inferior gluteal and internal pudendal arteries are often a common stem from the internal iliac, sometimes including the superior gluteal artery.

Surface anatomy. The inferior gluteal artery leaves the pelvis near the midpoint of a line joining the posterior superior iliac spine and the ischial tuberosity.

Branches. Inside the pelvis there are branches to the following:

- the piriformis, coccygeus and levator ani
- the perirectal fat, occasionally replacing the middle rectal artery
- the vesical fundus, seminal vesicles and prostate.

Outside the pelvis muscular branches supply the gluteus maximus, obturator internus, gemelli, quadratus femoris and the proximal parts of the hamstring muscles, anastomosing with the superior gluteal, internal pudendal, obturator and medial circumflex femoral arteries. *Coccygeal branches* run medially through the sacrotuberous ligament to supply the gluteus maximus and the structures attached to the coccyx. The *artery to the sciatic nerve* runs on the nerve for a short distance, then descends in it to the lower thigh. An *anastomotic branch* descends obliquely across obturator internus, gemelli and

quadratus femoris, to join the *cruciate anastomosis* (p. 1567) linking with the first perforating and medial and lateral circumflex femoral arteries. This may become an important route of collateral supply in cases of occlusion of the aorto-iliac system. An *articular branch*, usually from the anastomotic, is distributed to the hip joint. *Cutaneous branches* supply the buttock and back of the thigh.

Internal pudendal artery in the female

The internal pudendal in the female is naturally smaller but its origin, course and branches are similar, including the *posterior labial branches*, the *artery of the bulb* (distributed to the erectile tissue of the vestibular bulb and vagina), *deep artery of the clitoris*, supplying the corpus cavernosum, and a *dorsal artery* to the glans and prepuce of the clitoris.

Variations

Branches of the internal pudendal are sometimes derived from an *accessory pudendal*, usually a branch of the pudendal before its exit from the pelvis.
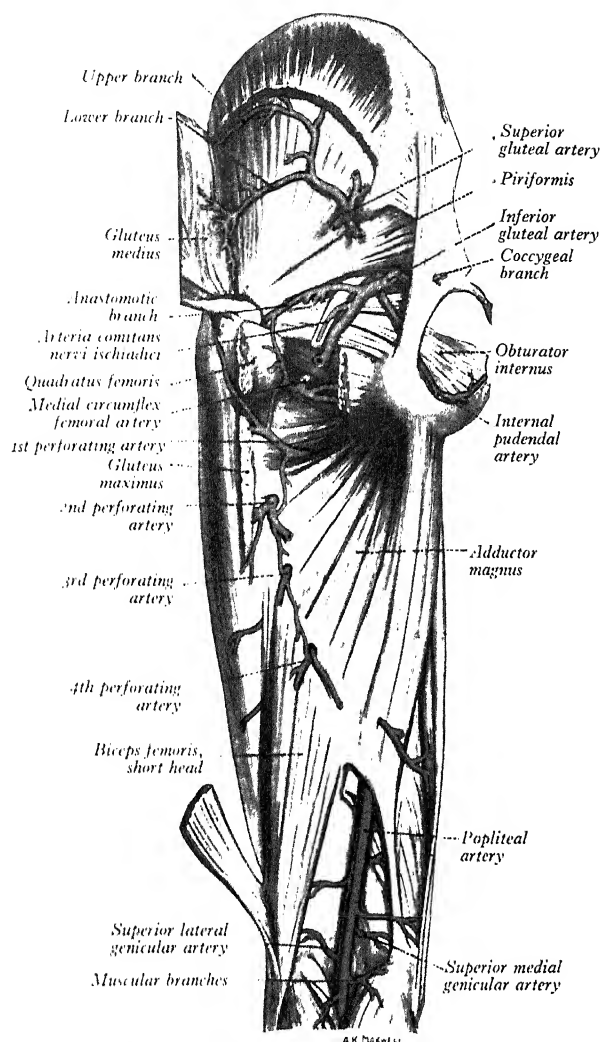
BRANCHES OF POSTERIOR TRUNK OF INTERNAL ILIAC ARTERY

Iliolumbar artery (**10.130**). This ascends laterally **anterior** to the sacro-iliac joint and lumbosacral trunk, **posterior** to the obturator nerve and external iliac vessels, to reach the medial border of psoas major, dividing behind it into the lumbar and iliac branches. The *lumbar branch* supplies the psoas major and quadratus lumborum, anastomoses with the fourth lumbar artery and sends a small *spinal branch* through the intervertebral foramen between the fifth lumbar and first sacral vertebrae, which supplies the cauda equina. The *iliac branch* supplies the iliacus; between the muscle and bone it anastomoses with the iliac branches of the obturator. A large nutrient branch enters an oblique canal in the ilium; others skirt the iliac crest, supplying the gluteal and abdominal muscles and anastomosing with the superior gluteal, circumflex iliac and lateral circumflex femoral arteries.

Lateral sacral arteries (**10.130**). These are from the posterior trunk of the internal iliac, usually as a superior and an inferior branch. The *superior* and larger passes medially into the first or second anterior sacral foramen, supplies the sacral vertebrae and contents of the sacral canal and escapes via the corresponding dorsal foramen to supply the skin and muscles dorsal to the sacrum. The *inferior lateral sacral artery* crosses obliquely anterior to the piriformis and the sacral anterior spinal rami, then descends lateral to the sympathetic trunk to anastomose with its fellow and the median sacral artery anterior to the coccyx. Its branches enter the anterior sacral foramina, distributed like those of the superior artery.

Superior gluteal artery (**10.129, 130, 135**). The largest branch of the internal iliac and the continuation of its posterior trunk, it runs back between the lumbosacral spinal trunk and the first sacral ramus or between the first and second rami, leaving the pelvis by the greater sciatic foramen above the piriformis and dividing into *superficial* and *deep branches*. In the pelvis it supplies the piriformis, obturator internus and an innominate nutrient artery. The superficial branch enters the deep surface of the gluteus maximus; its numerous branches supply the muscle and anastomose with the inferior gluteal, others perforating its tendinous medial attachment to supply the skin over the sacrum, anastomosing with the posterior branches of the lateral sacral arteries. The deep branch is between the gluteus medius and the bone, soon dividing into superior and inferior branches. The *superior* skirts the superior border of the gluteus minimus to the anterior superior iliac spine, anastomosing with the deep circumflex iliac artery and the ascending branch of the lateral circumflex femoral. The *inferior branch* traverses the gluteus minimus obliquely and supplies it and also the gluteus medius, anastomosing with the lateral circumflex femoral; a branch enters the trochanteric fossa to join the inferior gluteal and ascending branch of the medial circumflex femoral; other branches pierce the gluteus minimus to supply the hip joint.

The superior gluteal artery may arise from the internal iliac with the inferior gluteal and sometimes the internal pudendal.

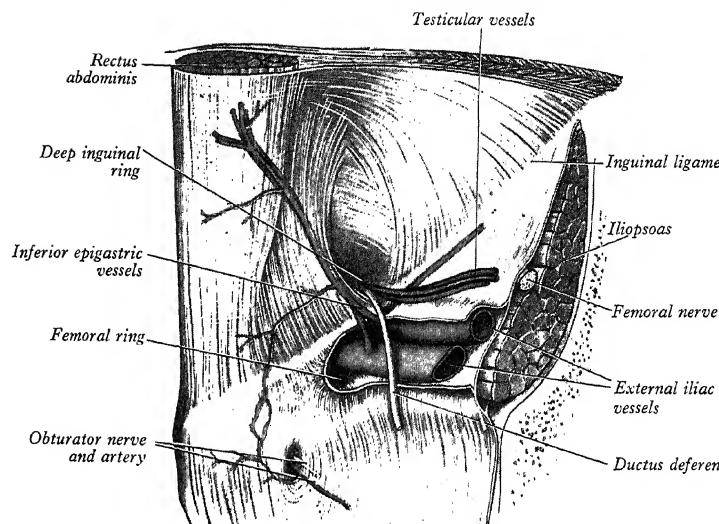*Surface anatomy.* The artery's pelvic exit corresponds to the

Upper branch

Lower branch

Gluteus
medius

Anastomotic
branch

Arteria comitans
nervi ischiadici

Quadratus femoris

Medial circumflex
femoral artery

1st perforating artery

Gluteus
maximus

2nd perforating
artery

3rd perforating
artery

4th perforating
artery

Biceps femoris,
short head

Superior lateral
genicular artery

Muscular branches

Superior gluteal artery

Piriformis

Inferior gluteal artery

Coccygeal branch

Obturator internus

Internal pudendal artery

Adductor magnus

Popliteal artery

Superior medial genicular artery

A.K. MAXWELL.

10.135 The arteries of the left gluteal and posterior femoral regions.

Rectus abdominis

Deep inguinal ring

Inferior epigastric vessels

Femoral ring

Obturator nerve and artery

Testicular vessels

Inguinal ligame

Iliopsoas

Femoral nerve

External iliac vessels

Ductus deferen

10.136 Dissection of the deep aspect of the lower part of the abdominal wall of the right side with the thinner posterior wall of the rectus sheath. The femoral and deep inguinal rings are displayed together with the vessels and other structures in relation to them and also the opening into the obturator canal.

junction of the upper and middle thirds of a line joining the posterior superior iliac spine to the apex of the greater trochanter.

The external iliac arteries (10.129–131, 136) are larger than the internal. Each descends laterally along the medial border of the psoas major from the common iliac bifurcation (anterior to the sacro-iliac joint at lumbosacral disc level) to a point midway between the anterior superior iliac spine and the symphysis pubis, entering the thigh posterior to the inguinal ligament to become the femoral artery.

Anteromedially the artery is related to the parietal peritoneum and extraperitoneal tissue, separating the right from the terminal ileum and often the appendix, the left from the sigmoid colon and coils of the small intestine. At its origin the artery may be crossed by the ureter, in females by ovarian vessels. Testicular vessels are anterior for some distance near its distal end, and it is crossed here by the genital branch of the genitofemoral nerve, the deep circumflex iliac vein and the ductus deferens or round ligament. **Posteriorly** the iliac fascia separates it from the medial border of the psoas major. The external iliac vein is partly posterior to its upper part, medial to it below. **Laterally** it is related to the psoas major, the iliac fascia lying between them. Numerous lymph vessels and nodes lie on its front and sides.

Branches. Apart from very small vessels to the psoas major and

neighbouring lymph nodes, the artery has no branches until the inferior epigastric and deep circumflex iliac arise near to its termination. Besides supplying the psoas major and neighbouring lymph nodes, the artery has inferior epigastric and deep circumflex iliac branches.

Inferior epigastric artery (7.84, 10.136). This leaves the external iliac just proximal to the inguinal ligament, curves forwards in extraperitoneal tissue, ascends obliquely along the medial margin of the deep inguinal ring, continues up to pierce the transversalis fascia and the attenuated part of the rectus sheath (p. 825) and ascends between the rectus abdominis and the posterior lamina of its sheath. It divides into numerous branches, which anastomose with those of the superior epigastric and lower posterior intercostal arteries. The artery thus skirts the deep inguinal ring inferomedially, passing posterior to the spermatic cord but separated from it by the transversalis fascia. It raises the parietal peritoneum of the anterior abdominal wall as the *lateral umbilical fold* (p. 1737). The ductus deferens, or round ligament, winds laterally round it. It supplies the following branches:

• The *cremasteric artery* (p. 1557) accompanies the spermatic cord, supplies the cremaster and other coverings of the cord and anastomoses with the testicular artery. In females it is small and accompanies the round ligament.
• A *pubic branch*, near the femoral ring, descends posterior to the pubis and anastomoses with the pubic branch of the obturator. In 20–30% of subjects, the pubic branches of the inferior epigastric are larger than, and replace, those of the obturator artery (p. 1560).
• *Muscular branches* supply the abdominal muscles and peritoneum, anastomosing with the circumflex iliac and lumbar arteries.
• *Cutaneous branches* perforate the aponeurosis of the external oblique, supply the skin and anastomose with branches of the superficial epigastric artery.

Variations. The artery may arise from the femoral and then ascend, anterior to the femoral vein, to the abdomen. It often arises from the external iliac artery in common with an abnormal obturator and, rarely, directly from the obturator artery.

Clinical anatomy. The inferior epigastric artery is a main route, through anastomosis with the internal thoracic, for collateral circulation after ligature of either the common or the external iliac arteries. It is **medial** to the neck of an oblique inguinal hernia but **lateral** to that of a direct inguinal hernia (p. 1560).

Deep circumflex iliac artery. This branches laterally from the external iliac almost opposite the inferior epigastric. It ascends 1563

laterally to the anterior superior iliac spine posterior to the inguinal ligament in a sheath formed by the junction of the transversalis and iliac fasciae. There it anastomoses with the ascending branch of the lateral circumflex femoral artery, pierces the transversalis fascia and skirts the internal lip of the iliac crest; about halfway it perforates the transversus abdominis and runs between this and the internal

oblique to anastomose with the iliolumbar and superior gluteal arteries. At the anterior superior iliac spine it has a large *ascending branch*, which runs between the internal oblique and the transversus, supplying them and anastomosing with the lumbar and inferior epigastric arteries.

The main artery of the thigh is the continuation of the external iliac, extending from the inguinal ligament to the distal border of the popliteus, where it divides into the anterior and the posterior tibial artery. Its proximal section, the femoral artery, lies among the knee extensor muscles; its continuation, the popliteal artery, is among the knee flexors.

FEMORAL ARTERY

The femoral artery (10.137–142), a continuation of the external iliac, begins behind the inguinal ligament, midway between the anterior superior iliac spine and the pubic symphysis, descends along the anteromedial part of the thigh in the femoral triangle and becomes the popliteal as it passes through the adductor canal, an opening in the adductor magnus near the junction of the middle and distal thirds of the thigh. Its first 3 or 4cm are enclosed, with its vein, in the femoral sheath.

FEMORAL SHEATH

Distal prolongations, behind the inguinal ligament, of the transversalis fascia, anterior to the femoral vessels, and of the iliac fascia, posterior, together form a short funnel, wider proximally, its distal end fusing with the vascular fascia 3 or 4cm distal to the ligament (10.137). At birth the sheath is shorter, elongating when extension at the hips becomes habitual. Its vertical lateral wall is perforated by the femoral branch of the genitofemoral nerve; the medial wall slopes laterally and is pierced by the great (long) saphenous vein and lymphatic vessels. Like the carotid sheath, the femoral sheath encloses a mass of connective tissue in which the vessels are embedded. Three compartments are described: a lateral one containing the

Lateral femoral cutaneous nerve

Inguinal ligament

ILIACUS

Femoral nerve
Femoral branch of genitofemoral nerve
Femoral artery
Femoral sheath
Femoral vein
Femoral canal
Lacunar ligament

PSOAS MAJ.

PECTINEUS

10.137 The structures passing posterior to the right lacunar ligament: inferior (distal) aspect. Note the lacuna musculorum and the lacuna vasorum.

femoral artery; an intermediate one for the femoral vein; medial and smallest is the femoral canal, containing the lymph vessels and a lymph node embedded in areolar tissue, probably to allow the vein to distend. This canal is conical, about 1.25cm in length; its proximal end is the outer femoral ring, bounded in front by the inguinal ligament, behind by the pectineus and its fascia, medially by the crescentic edge of the lacunar ligament and laterally by the femoral vein (p. 1789). The spermatic cord, or the round ligament, is just above its anterior margin; the inferior epigastric vessels are near its anterolateral rim. It is larger in women than in men due partly to the greater breadth of the pelvis, partly to the smaller size of the femoral vessels, in women. The ring is filled by condensed extraperitoneal tissue, the femoral septum, covered by the parietal peritoneum (p. 1788). The femoral septum is traversed by numerous lymph vessels connecting the deep inguinal to the external iliac lymph nodes.

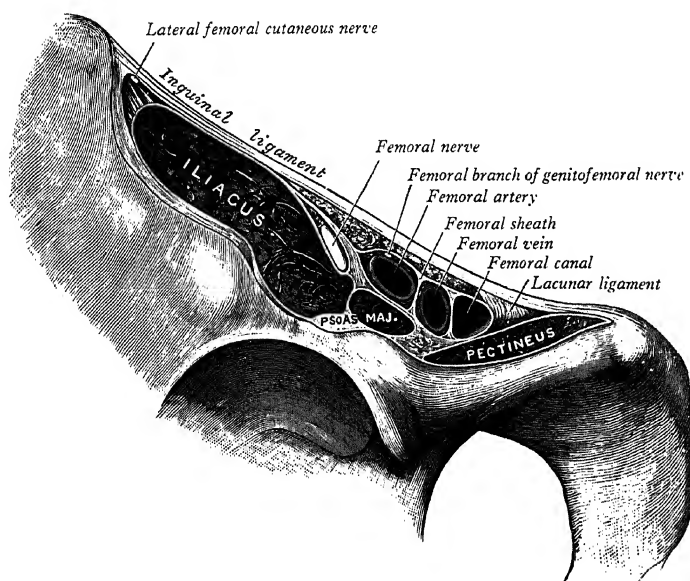### Femoral triangle (10.138–140)

The femoral triangle is a depressed area of the thigh lying distal to the inguinal fold. Its apex is distal, its limits being laterally the medial margin of sartorius, medially the medial margin of adductor longus; proximally (the base) is the inguinal ligament. Its floor is provided laterally by iliacus and psoas major, medially by pectineus and adductor longus. The femoral vessels, passing from midbase to apex, are in the deepest part of the triangle. Lateral to the artery the femoral nerve divides. The triangle also contains fat and lymph nodes.

Relations of the femoral artery in the femoral triangle (10.140). **Anterior** to the artery are the skin, superficial fascia, superficial inguinal lymph nodes, fascia lata, femoral sheath, superficial circumflex iliac vein (crossing in the superficial fascia) and the femoral branch of the genitofemoral nerve (at first lateral then anterior). Near the apex the medial femoral cutaneous nerve crosses the artery from the lateral to the medial side. **Posterior** are the femoral sheath and the tendons of psoas, pectineus and adductor longus. The artery is separated from the hip joint by the tendon of psoas major, from the pectineus by the femoral vein and profunda vessels and from the adductor longus by the femoral vein. Proximally, the nerve to the pectineus passes medially behind the artery; **lateral** to it is the femoral nerve. The femoral vein is **medial** in the proximal part of the triangle, becoming posterior near its apex, distally.
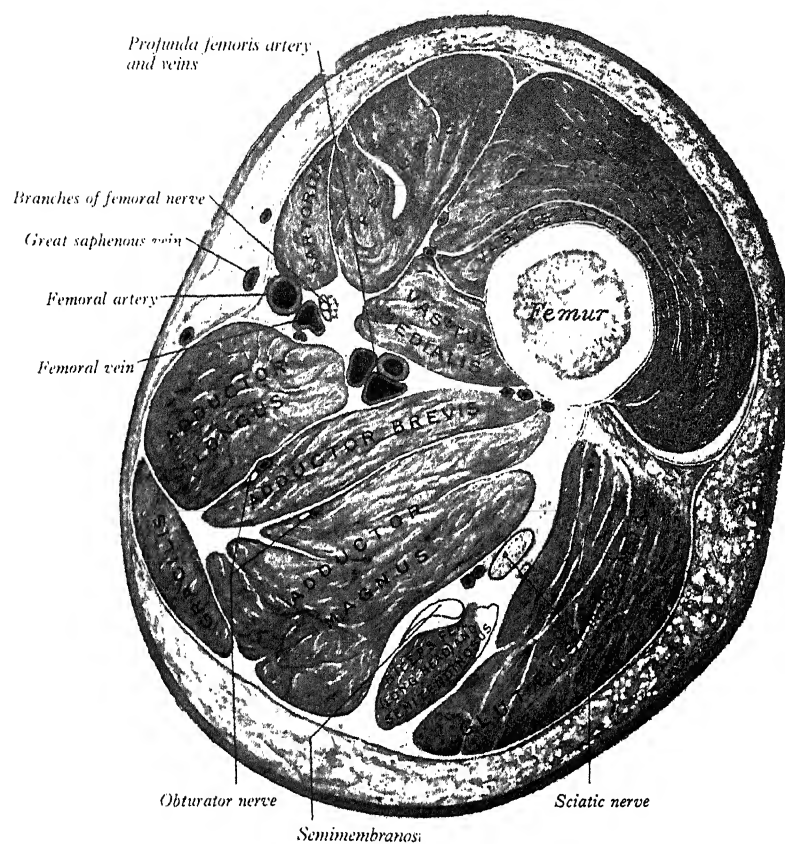
Adductor canal (10.138–140). It is an aponeurotic tunnel in the middle third of the thigh, from the apex of the femoral triangle to the opening in adductor magnus, through which femoral vessels reach the popliteal fossa. Triangular in section, it is bounded **anterolaterally** by vastus medialis, **posteriorly** by adductor longus, distally by adductor magnus and **anteromedially** by a strong aponeurosis extending between the adductors across the vessels to vastus medialis. The sartorius is anterior. The canal contains the femoral artery and vein, the saphenous nerve, and the nerve to vastus medialis until it enters its muscle.

Relations of the femoral artery in the adductor canal (10.139–141). **Anterior** to the artery are the skin, superficial and deep fasciae, sartorius and fibrous roof of the canal. The saphenous nerve is first lateral, then anterior and finally medial. **Posterior** are the adductor longus and adductor magnus; the femoral vein is also posterior proximally, but becoming lateral distally. Anterolateral are the vastus medialis and its nerve.
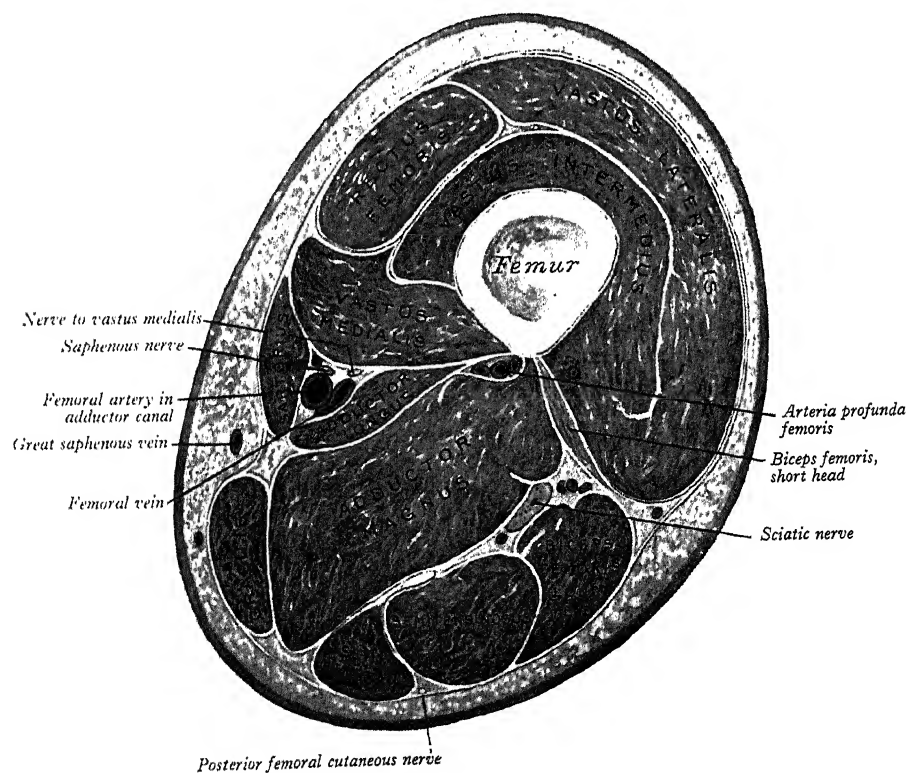
Surface anatomy. The artery corresponds to the proximal two-thirds of a line drawn from the midpoint between the anterior-superior iliac spine and the pubic symphysis to the adductor tubercle

Profunda femoris artery and veins

Branches of femoral nerve

Great saphenous vein

Femoral artery

Femoral vein

Femur

Obturator nerve

Sciatic nerve

Semimembranos

10.138 Transverse section through the right thigh at the level of the apex of the femoral triangle: superior (proximal) aspect. About three-fifths of the natural size. The cutaneous nerves are omitted.

Nerve to vastus medialis

Saphenous nerve

Femoral artery in adductor canal

Great saphenous vein

Femoral vein

Femur

Arteria profunda femoris

Biceps femoris, short head

Sciatic nerve

Posterior femoral cutaneous nerve

10.139 Transverse section through the middle of the right thigh: superior (proximal) aspect. About three-fifths of the natural size.

Superficial epigastric
artery
Deep circumflex
iliac artery
Superficial circumflex
iliac artery
Tensor fasciae latae ·

Medial femoral
circumflex artery
Lateral femoral
circumflex artery
Arteria profunda
femoris

Rectus femoris –

Vastus lateralis—

Superficial external
pudendal artery
Deep external
pudendal artery
Great saphenous vein
Femoral artery
Femoral vein
Sartorius

Adductor longus

Gracilis

Adductor magnus

Vastus medialis

Sartorius

A·K·MAXWELL·

10.140   The right femoral vessels and some of their branches.

Profunda
femoris
artery

Femoral
artery

10.141   Femoral arteriogram. (Supplied by Shaun Gallagher, Guy's Hospital; photography by Sarah Smith.)

above the medial condyle of the femur, with the thigh semiflexed, abducted and laterally rotated. Its pulsation is easily palpable in its proximal course.
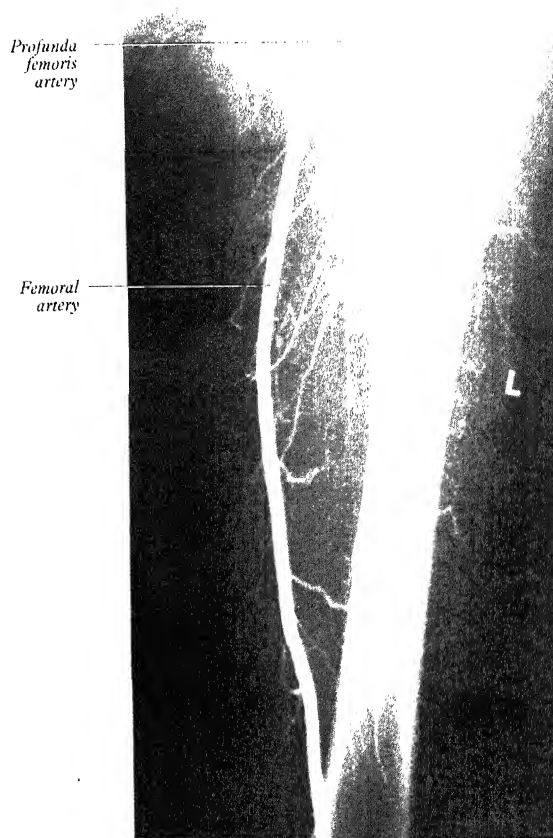
Variations. Rarely, the femoral artery divides, distal to the origin of the arteria profunda femoris, into two trunks reuniting near the adductor opening. It may be replaced by the inferior gluteal artery, accompanying the sciatic nerve to the popliteal fossa and representing a proximal persistence of the original axial artery (p. 318); the external iliac is then small, ending as the arteria profunda femoris.

Clinical anatomy. Compression of the femoral artery is most effective just distal to the inguinal ligament, where it is superficial and separated from the bone (iliopubic eminence) only by the psoas tendon.

Branches. These are as follows:

Superficial epigastric artery (10.140). Arising anteriorly from the femoral about 1 cm distal to the inguinal ligament, it traverses the cribriform fascia to ascend anterior to the ligament and run in the abdominal superficial fascia almost to the umbilicus. It supplies the superficial inguinal lymph nodes and superficial fascia and skin, anastomosing with branches of the inferior epigastric and its fellow.

Superficial circumflex iliac artery (10.140). This is the smallest superficial branch of the femoral; it arises near or with the superficial epigastric. Usually emerging through the fascia lata, lateral to the saphenous opening, it turns laterally distal to the inguinal ligament towards the anterior–superior iliac spine; it supplies the skin, super-

ficial fascia and superficial inguinal lymph nodes, anastomosing with the deep circumflex iliac, superior gluteal and lateral circumflex femoral arteries.

Superficial external pudendal artery (10.140). It arises medially from the femoral, close to the preceding branches. Emerging from the cribriform fascia, it passes medially, usually deep to the great saphenous vein, across the spermatic cord (or round ligament) to supply the lower abdominal, penile, scrotal or labial skin, anastomosing with branches of the internal pudendal.

Veins accompanying the superficial epigastric, superficial circumflex iliac and external pudendal arteries join the great saphenous vein before it enters the saphenous opening.

Deep external pudendal artery (10.140). This artery passes medially across the pectineus and anterior or posterior to the adductor longus, covered by fascia lata, piercing it to supply the skin of the perineum and scrotum or labium majus; its branches anastomose with the posterior scrotal or labial branches of the internal pudendal.

Muscular branches. These supply the sartorius, the vastus medialis and the adductors.

ARTERIA PROFUNDA FEMORIS

The arteria profunda femoris is a large branch arising laterally from the femoral about 3.5 cm distal to the inguinal ligament (10.139–142). At first lateral to the femoral artery, it spirals posterior to this and the femoral vein to the medial side of the femur; it passes between pectineus and adductor longus, then between the latter and adductor brevis and then descends between adductor longus and adductor magnus to finally pierce the latter and anastomose with the upper muscular branches of the popliteal. This terminal part is sometimes named the *fourth perforating artery.*

The deep femoral artery is the main supply to the adductor,

extensor and flexor muscles; it also anastomoses with the internal and external iliac arteries above and the popliteal artery below.

Relations. Posterior, in proximodistal order, are: the iliacus, pectineus, adductor brevis and adductor magnus. Anterior are the femoral and profunda veins and distally the adductor longus, separating it from the femoral artery. Laterally vastus medialis separates its proximal part from the femur.

Variations. Its origin is sometimes medial, or rarely posterior on the femoral artery; if the former, it may cross anterior to the femoral vein and then pass backwards around its medial side.

Branches. These are as follows:

Lateral circumflex femoral artery (10.142). A lateral branch near the root of the profunda, it inclines laterally between divisions of the femoral nerve, posterior to sartorius and rectus femoris, dividing into ascending, transverse and descending branches. It may arise from the femoral. The *ascending branch* ascends along the intertrochanteric line, under the tensor fasciae latae, lateral to the hip joint; it anastomoses with the superior gluteal and deep circumflex iliac arteries, supplying the greater trochanter, and forms an anastomotic ring round the femoral neck with branches of the medial circumflex femoral; from this ring the femoral neck and head are supplied. The *descending branch*, sometimes direct from the profunda or the femoral, descends posterior to the rectus femoris, along the anterior border of the vastus lateralis, which it supplies: a long ramus descends in vastus lateralis to the knee, anastomosing with the lateral superior genicular branch of the popliteal, accompanied by the nerve to vastus lateralis. The *transverse branch*, the smallest, passes laterally anterior to vastus intermedius, pierces vastus lateralis to wind round the femur, just distal to the greater trochanter, anastomosing with the medial circumflex, inferior gluteal and first perforating arteries (cruciate anastomosis).

Medial circumflex femoral artery (10.142). Originating usually from the posteromedial aspect of the profunda but often the femoral artery, this artery supplies the adductor muscles and curves medially round the femur between pectineus and psoas major and then obturator externus and adductor brevis, finally appearing between quadratus femoris and upper border of adductor magnus, dividing into transverse and ascending branches. The *transverse branch* takes part in the cruciate anastomosis. The *ascending branch* ascends on the tendon of the obturator externus, anterior to the quadratus femoris, to the trochanteric fossa, where it anastomoses with branches of the gluteal and lateral circumflex femoral arteries. An acetabular branch at the proximal edge of the adductor brevis enters the hip joint under the transverse acetabular ligament with one from the obturator artery; it supplies the fat in the fossa, and reaches the femoral head along its ligament. For blood supply of the proximal end of the femur consult Crock (1965).

Perforating arteries (10.135). Usually three, they perforate the attachment of adductor magnus to reach the thigh's flexor aspect. They pass close to the linea aspera under small tendinous arches and issue muscular, cutaneous and anastomotic branches. Diminished, they pass deep to the short head of biceps femoris (the first usually through the attachment of gluteus maximus), traverse the lateral intermuscular septum and enter vastus lateralis. The first arises proximal to the adductor brevis, the second anterior and the third distal. The *first perforating artery* passes back between the pectineus and adductor brevis (sometimes through the latter), piercing the adductor magnus near the linea aspera to supply adductor brevis, adductor magnus, biceps femoris and gluteus maximus, anastomosing with the inferior gluteal, medial and lateral circumflex femoral and second perforating arteries. The larger *second perforating artery*, often arising with the first, pierces the attachments of adductor brevis and magnus, divides into the ascending and descending branches supplying the posterior femoral muscles and anastomoses with the first and third perforating arteries. The *femoral nutrient artery* usually arises from it; when two nutrient arteries exist, they usually come from the first and third. The *third perforating artery* starts distal to adductor brevis, pierces the attachment of adductor magnus and divides into branches to the posterior femoral muscles; it anastomoses proximally with the perforating arteries, distally with the end of the profunda and muscular branches of the popliteal. The femoral nutrient artery may arise from it. Side branches of the diaphyseal nutrient and other branches of the profunda also provide subsidiary cortical arteries (Crock 1967).
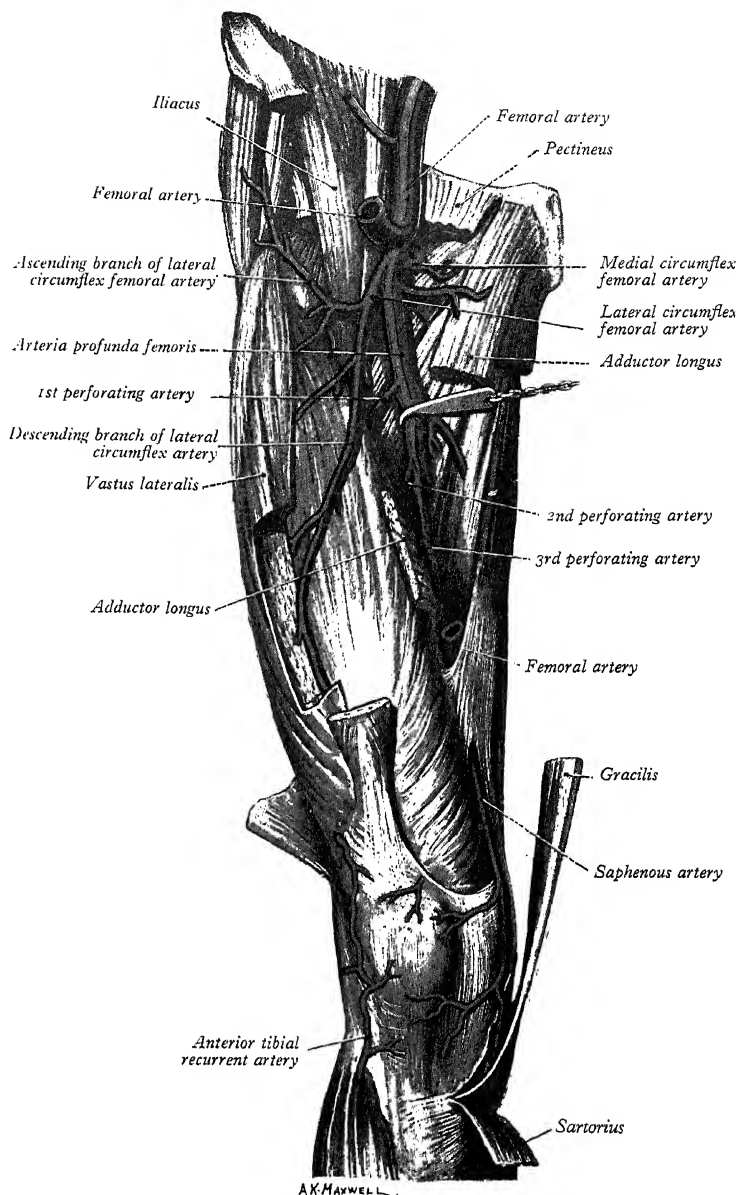
10.142 The right profunda femoris artery and its branches.

The end of arteria profunda femoris is the *fourth perforating artery*. The perforating arteries form a double chain of anastomoses:

(1) in the adductor muscles
(2) near the linea aspera.

Muscular branches. These are numerous and arise from the arteria profunda femoris; some end in the adductors, others pierce adductor magnus, supply the flexors and anastomose with the medial circumflex femoral artery and superior muscular branches of the popliteal. The profunda is thus the **main** supply to the femoral muscles.

Anastomosis on the back of the thigh. This important chain of anastomoses stretches from the gluteal region to the popliteal fossa, formed in proximodistal order by anastomoses between:

- gluteal arteries and terminals of the medial circumflex femoral
- circumflex femoral arteries and the first perforating artery
- perforating arteries and each other
- the fourth perforating artery and the superior muscular branches of the popliteal.

155

Descending genicular artery (10.146). It arises from the femoral just proximal to the adductor opening, at once supplying a saphenous branch and then descending in the vastus medialis, anterior to the tendon of adductor magnus, to the medial side of the knee, anastomosing with the medial superior genicular artery. Muscular branches supply vastus medialis and adductor magnus and have articular branches, which anastomose round the knee joint. One articular branch crosses above the femoral patellar surface, forming an arch with the lateral superior genicular artery and supplying the knee joint. The saphenous branch emerges distally through the roof of the adductor canal to accompany the saphenous nerve to the medial side of the knee. Passing between sartorius and gracilis it supplies the skin of the proximomedial area of the leg, anastomosing with the medial inferior genicular artery.

Collateral circulation. After ligation of the femoral artery proximal to the origin of the arteria profunda femoris, the main anastomotic channels available are:

- superior and inferior gluteal branches of the internal iliac with the medial and lateral circumflex femoral and the first perforating branch of the arteria profunda femoris
- the obturator branch of the internal iliac with the medial circumflex femoral of the arteria profunda femoris
- the internal pudendal branch of the internal iliac with superficial and deep external pudendal branches of the femoral
- a deep circumflex iliac branch of the external iliac with the lateral circumflex femoral branch of the arteria profunda femoris and the superficial circumflex iliac branch of the femoral
- the inferior gluteal branch of the internal iliac with perforating branches of the arteria profunda femoris.
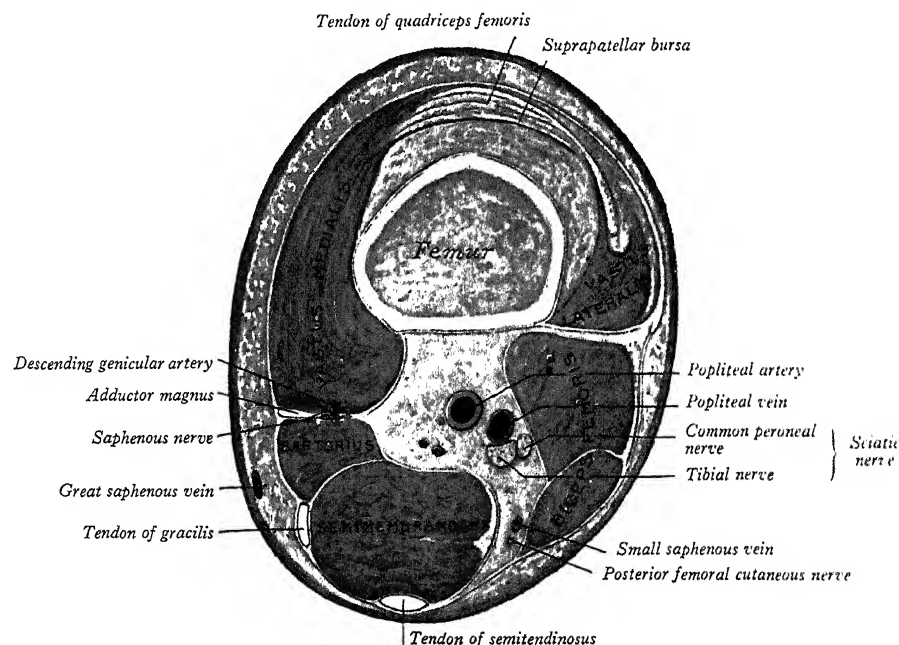
POPLITEAL FOSSA

The popliteal fossa is a rhomboidal region posterior to the knee joint, more apparent when disturbed by dissection (7.136, 8.384, 8.385, 10.144). **Lateral** are proximally the biceps femoris and distally the plantaris and lateral head of gastrocnemius; **medial** and proximally are the semitendinosus and semimembranosus, and distally the medial head of the gastrocnemius; **anterior** are the femoral popliteal surface, oblique popliteal ligament, back of the proximal end of the tibia and the fascia covering the popliteus, collectively forming a so-called floor. The fossa is covered **posteriorly** by the

popliteal fascia. (Note that 'popliteal fascia' refers to part of the general investing layer of deep fascia that forms a 'roof' for the fossa; to be carefully distinguished from the 'fascia of popliteus' which forms part of the floor.)
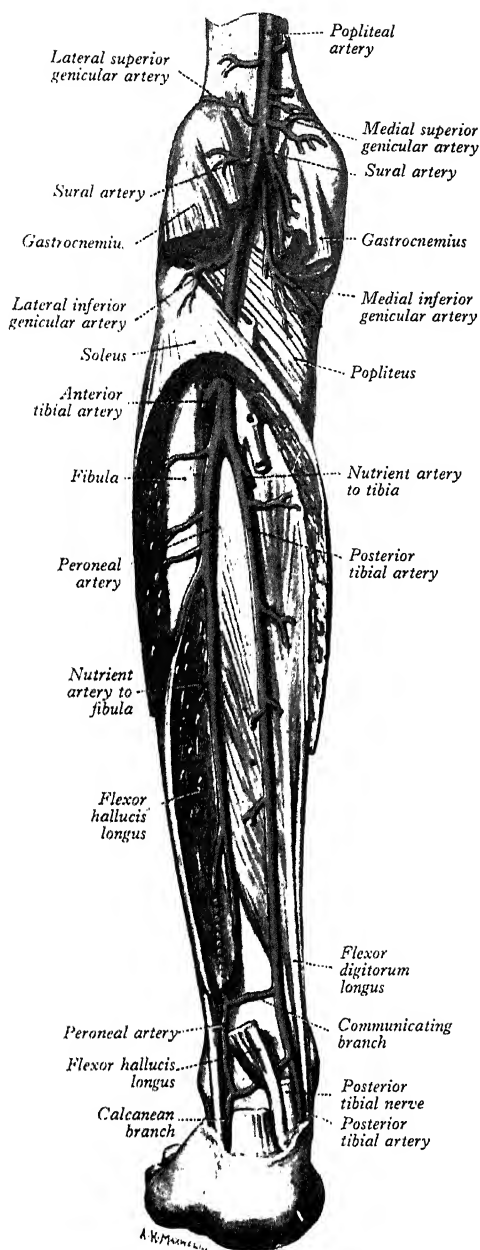
Contents (8.260, 10.144). Until disturbed, the popliteal fossa is about 2.5 cm wide and its contents are largely hidden, especially in its distal part, where the heads of gastrocnemius are in contact. When its boundaries are separated its contents are seen to be the popliteal vessels, the tibial and common peroneal nerves, the small saphenous vein, posterior femoral cutaneous nerve, an obturator articular branch, lymph nodes and fat. The tibial nerve descends centrally immediately anterior to the popliteal fascia, crossing the vessels posteriorly from lateral to medial. The common peroneal nerve descends laterally near the tendon of biceps femoris. Popliteal vessels are deep on the floor, the vein superficial to the artery, and united by dense areolar tissue. The vein is thick-walled, proximally lateral to the artery, and crossing to its medial side distally; sometimes it is double with the artery between the veins, the latter usually being interconnected. An articular branch from the obturator nerve descends on the artery to the knee. Six or seven popliteal lymph nodes are embedded in the fat, one under the popliteal fascia near the end of the small saphenous vein, one between the popliteal artery and knee joint, others around the popliteal vessels.

The popliteal artery (10.143–145), continuing the femoral, traverses the popliteal fossa; from the opening in adductor magnus it descends laterally to the intercondylar fossa, inclining obliquely to the distal border of the popliteus, where it divides into the *anterior* and *posterior tibial arteries* (10.144). This division is at the proximal end of the crural interosseous space (which is asymmetrical) between the wide tibial metaphysis and the slender fibular metaphysis. Thus the popliteal artery extends from the medial border of the femur to the laterally placed interosseous space, accounting for its oblique descent (10.145).

Relations. Anterior, proximodistally, is fat covering the femoral popliteal surface, the capsule of the knee joint, and the fascia of popliteus. Posterior are, proximally, the semimembranosus and, distally, the gastrocnemius and plantaris. At intermediate level the artery is separated from the skin and fasciae by fat and crossed from

Tendon of quadriceps femoris
Suprapatellar bursa

Descending genicular artery
Adductor magnus
Saphenous nerve
Great saphenous vein
Tendon of gracilis

Popliteal artery
Popliteal vein
Common peroneal nerve
Tibial nerve
Sciatic nerve
Small saphenous vein
Posterior femoral cutaneous nerve

Tendon of semitendinosus

10.143 Transverse section through the right thigh, 4 cm above the adductor tubercle of the femur: superior (proximal) aspect. About three-fifths of the natural size.
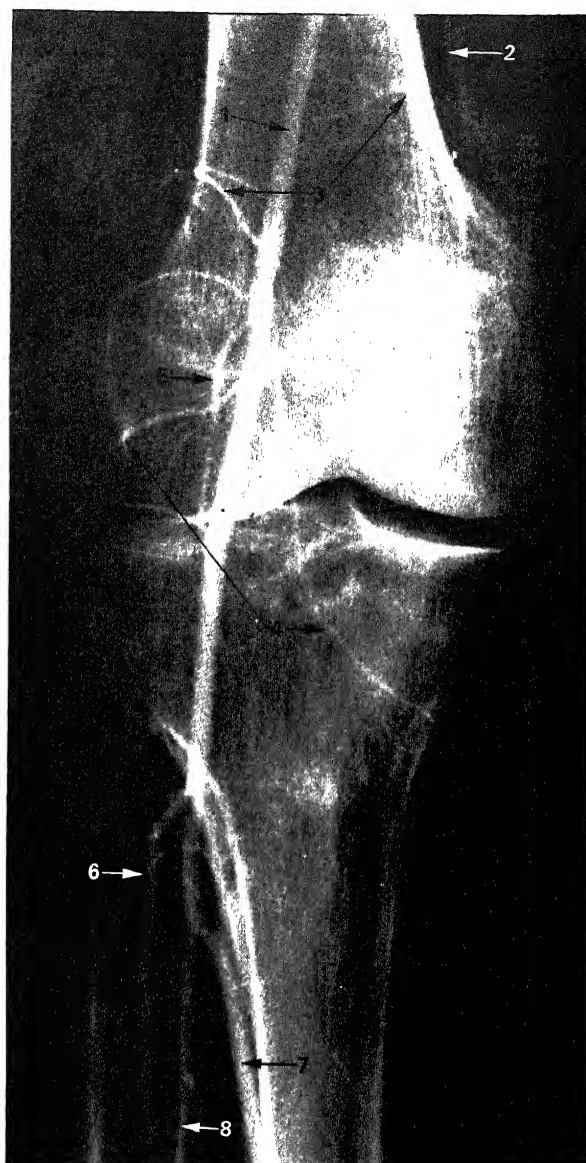
10.144 The left popliteal, posterior tibial and peroneal arteries: dorsal aspect.

10.145 Popliteal arteriogram: anteroposterior view of adult male of 63 years. The following arteries can be identified: 1. popliteal; 2. descending genicular; 3. superior medial and lateral genicular; 4. inferior medial and lateral genicular; 5. middle genicular; 6. anterior tibial; 7. posterior tibial; 8. peroneal. Note the (normal) obliquity of the popliteal artery.

lateral to medial by the tibial nerve and popliteal vein, the vein veing between the nerve and artery and adherent to the latter. **Lateral** are proximally the biceps femoris, tibial nerve, popliteal vein and lateral femoral condyle and distally the plantaris and lateral head of gastrocnemius. **Medial** are the semimembranosus and medial femoral condyle and distally the tibial nerve, popliteal vein and medial head of gastrocnemius. Relations of the popliteal lymph nodes are described on page 1616.

Variations. The artery may divide into terminal branches **proximal** to the popliteus, the anterior tibial artery then descending **anterior** to the muscle. Sometimes it divides into the anterior tibial and peroneal arteries, the posterior tibial being absent or rudimentary; it may divide into the anterior and posterior tibial and peroneal.

Surface anatomy. The popliteal artery is approximately represented as extending from the junction of the middle and lower thirds of the thigh, 2.5 cm medial to its posterior midline, to the

midpoint between the femoral condyles, continuing inferolaterally to the level of the tibial tuberosity, medial to the fibular neck.
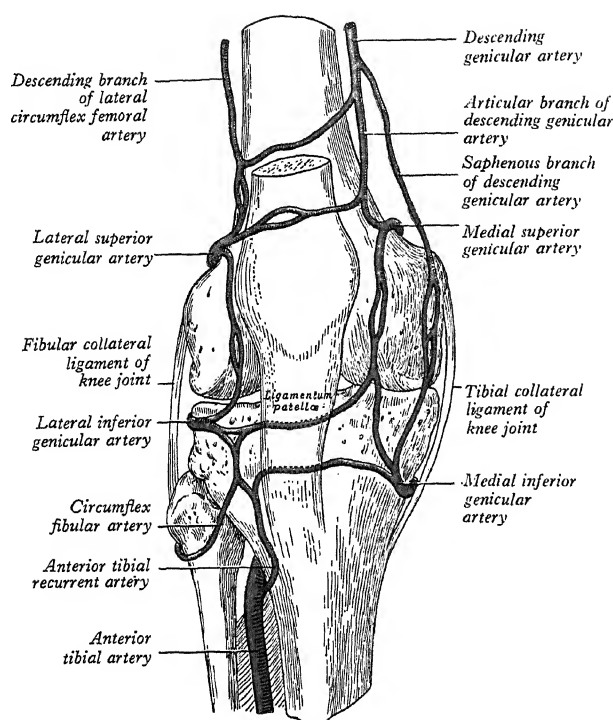
Branches. These are the cutaneous, muscular and genicular branches which reach the tibiofibular interosseous gap.

Cutaneous branches. They leave the popliteal or its side branches, descend between the heads of gastrocnemius and perforate the deep fascia to supply the skin on the back of the leg; one usually accompanies the small saphenous vein.

Superior muscular branches. Two or three in number, they arise proximally and pass to the adductor magnus and femoral flexors, anastomosing with the termination of the arteria profunda femoris.

Sural arteries. Two in number, these are large and arise behind the knee joint to supply gastrocnemius, soleus and plantaris.

Superior genicular arteries (10.144, 146). They diverge from the popliteal, curving round proximal to both femoral condyles, to the anterior aspect of the knee. The *medial superior genicular artery* lies

156

10.146 The arterial anastomosis around the knee joint (schematic).

the medial and lateral genicular, descending genicular, the descending branch of the lateral circumflex femoral, circumflex fibular and the anterior and posterior tibial recurrent arteries.

ANTERIOR TIBIAL ARTERY

The anterior tibial artery is the terminal branch of the popliteal and arises at the distal border of the popliteus (10.144–148). At first in the flexor compartment, it passes between the heads of tibialis posterior and through the oval aperture in the proximal part of the interosseous membrane (p. 712) to the extensor region, passing medial to the fibular neck. Descending anteriorly on the membrane it approaches the tibia and, distally, lies anterior to it (10.149). At the ankle it is midway between the malleoli, continuing on the dorsum of the foot as the *arteria dorsalis pedis*.

Relations. In its proximal two-thirds the artery descends on the interosseous membrane, in its distal third anterior to the tibia and ankle joint. Proximally it is between tibialis anterior and extensor

under semimembranosus and semitendinosus, proximal to the medial head of gastrocnemius and deep to the tendon of adductor magnus. It divides into a branch to the vastus medialis which anastomoses with the descending genicular and medial inferior genicular arteries, and one ramifying on the femur and anastomosing with the lateral superior genicular artery. Its size varies inversely with that of the descending genicular. The *lateral superior genicular artery* passes under the tendon of biceps femoris, dividing into superficial and deep branches; the superficial supplies the vastus lateralis, anastomosing with the descending branch of the lateral circumflex femoral and lateral inferior genicular; the deep branch anastomoses with the medial superior genicular, forming an anterior arch across the femur with the descending genicular.

Middle genicular artery. This small artery arises from the popliteal near the posterior centre of the knee joint; it pierces the oblique popliteal ligament to supply the cruciate ligaments and synovial membrane.

Inferior genicular arteries (10.144, 146). They arise from the popliteal deep to the gastrocnemius. The medial is deep to its medial head, descending along the proximal margin of the popliteus, which it supplies, and passing inferior to the medial tibial condyle and under the tibial collateral ligament, at the anterior border of which it ascends anteromedial to the joint; it supplies this and the tibia, anastomosing with the lateral inferior and medial superior genicular arteries and also with the anterior tibial recurrent artery and saphenous branch of the descending genicular. The lateral inferior genicular artery runs laterally across the popliteus and forwards over the fibula's head to the front of the knee joint, passing under the lateral head of gastrocnemius, the fibular collateral ligament and tendon of biceps femoris. Its branches anastomose with the medial inferior and lateral superior genicular, anterior and posterior tibial recurrent and circumflex fibular arteries.
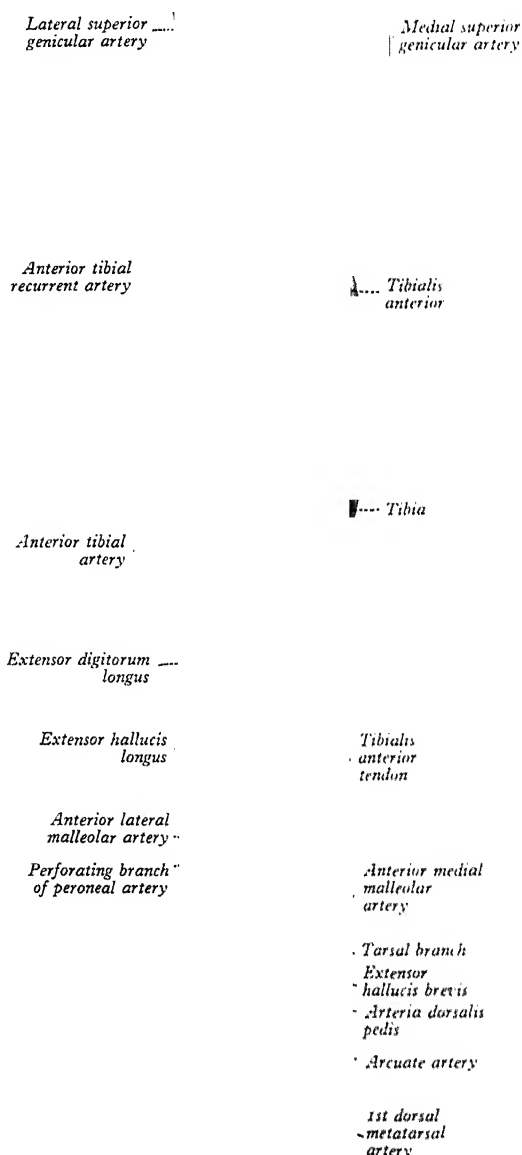
Genicular anastomosis

Around the patella and femoral and tibial condyles an intricate anastomosis exists. A superficial network spreads between the fascia and skin around the patella and in the fat deep to the ligamentum patellae. A deep network lies on the femur and tibia near the adjoining articular surfaces, supplying the bone and marrow, the articular capsule and synovial membrane. The vessels involved are

10.147 The right anterior tibial and dorsalis pedis arteries. A large part of the tibialis anterior has been excised and the extensor hallucis longus retracted laterally to expose the anterior tibial artery.

10.148 Transverse section through the right leg, about 10 cm below the knee joint: superior (proximal) aspect. At a slightly lower level the flexor digitorum longus intervenes between the soleus and the fascia on the posterior surface of the tibialis posterior.

longus, then between tibialis anterior and extensor hallucis s. At the ankle it is crossed superficially from the lateral side by the tendon of extensor hallucis longus and is then between this and the first tendon of the extensor digitorum longus. Its proximal two-thirds are covered by adjoining muscles and deep fascia, its distal third by the skin, fasciae and extensor retinacula. Venae comitantes accompany it. The deep peroneal nerve, curling laterally round the fibular neck, reaches the lateral side of the artery where it enters the extensor region but in the middle third of the leg becomes anterior to it and distally again becomes lateral.

Surface anatomy. Surface projection of the anterior tibial artery begins 2.5 cm distal to the medial side of the fibular head and ends midway between the malleoli. It can be felt pulsating lateral to the tendon of extensor hallucis longus.

Variations. This vessel may be small or even absent, replaced by perforating branches from the posterior tibial or the perforating branch of the peroneal. It occasionally deviates laterally, regaining its usual position at the ankle.

Branches. These are the anterior and posterior tibial recurrent; muscular; and anterior medial and lateral malleolar.

Posterior tibial recurrent artery. It is an inconstant branch, which arises before the anterior tibial reaches the extensor compartment, ascending anterior to the popliteus with the muscle's recurrent nerve, anastomosing with the inferior genicular branches of the popliteal. It supplies the superior tibiofibular joint.

Anterior tibial recurrent artery (10.147). Arising near the preceding vessel, it ascends in tibialis anterior, ramifies on the front and sides of the knee joint and joins the patellar network, anastomosing with the genicular branches of the popliteal and circumflex fibular arteries.

Muscular branches. These numerous branches supply the adjacent muscles; some pierce the deep fascia to supply the skin, others traverse the interosseous membrane to anastomose with branches of the posterior tibial and peroneal arteries.

Anterior medial malleolar artery (10.147, 150). It arises about 5 cm proximal to the ankle, passing posterior to the tendons of extensor hallucis longus and tibialis anterior medial to the joint, where it joins branches of the posterior tibial and medial plantar arteries.

Anterior lateral malleolar artery (10.147, 150). This artery pro-
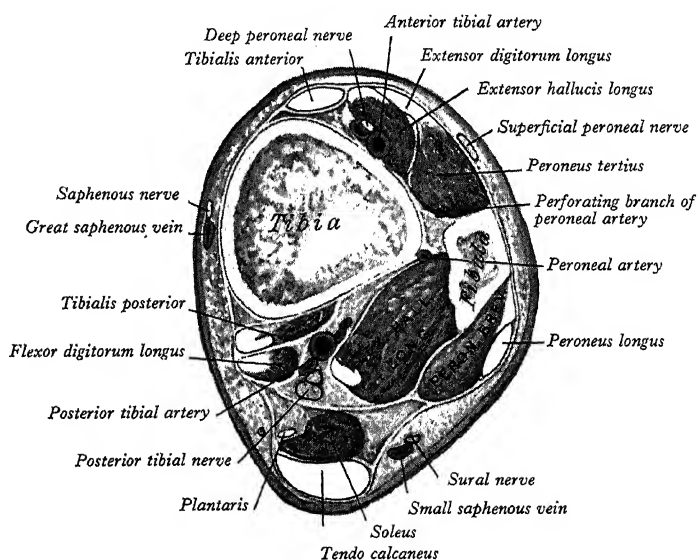
10.149 Transverse section through the right leg, about 6 cm above the tip of the medial malleolus: superior (proximal) aspect.

157

Peroneal artery

Posterior tibial artery

Anterior tibial artery

Perforating branch of peroneal artery

Anterior medial malleolar artery

Communicating branch

Anterior lateral malleolar artery

Lateral tarsal artery

Arteria dorsalis pedis

Posterior medial malleolar branch of posterior tibial artery

Medial plantar artery

Lateral plantar artery

Calcanean branches of posterior tibial and lateral plantar arteries

Calcanean branches of peroneal artery

Arcuate artery

10.150 The arterial anastomoses of the ankle, tarsus and metatarsus.

ceeds posterior to the tendons of extensor digitorum longus and peroneus tertius to the lateral side of the ankle, anastomosing with the perforating branch of the peroneal and ascending branches of the lateral tarsal artery.

Anastomosis at the ankle joint (10.150). This consists of vascular networks around the malleoli. The *medial malleolar network* is formed by the anterior medial malleolar branch of the anterior tibial, the medial tarsal branches of the arteria dorsalis pedis, the malleolar and calcaneal branches of the posterior tibial and branches of the medial plantar artery. The *lateral malleolar network* is formed by the anterior lateral malleolar branch of the anterior tibial, lateral tarsal branch of arteria dorsalis pedis, the perforating and calcaneal branches of the peroneal and side branches of the lateral plantar artery.

Arteria dorsalis pedis

The dorsal artery of the foot (10.147), it is the continuation of the anterior tibial distal to the ankle. It passes medially along the dorsum to the proximal end of the first intermetatarsal space, where it turns into the sole between the heads of the first dorsal interosseous muscle to complete the plantar arch, where it provides the first plantar metatarsal artery.

Relations. The dorsal artery successively crosses the talocrural articular capsule, talus, navicular and intermediate cuneiform and their ligaments; **superficial** are the skin, fasciae, inferior extensor retinaculum and, near its termination, extensor hallucis brevis. **Medial** is the tendon of extensor hallucis longus, **lateral** the medial tendon of extensor digitorum longus and medial terminal branch of the deep peroneal nerve.

Surface anatomy. The pulsation of the dorsal artery of the foot is palpable from the midpoint between the malleoli to the proximal end of the first intermetatarsal space.

Variations. The artery may be larger to compensate for a small lateral plantar artery or replaced by a large perforating branch of the peroneal. It often diverges laterally from its usual route.

Branches. These are the tarsal, arcuate and first dorsal metatarsal arteries.

Tarsal arteries. These two arteries, lateral and medial (10.147), arise as the arteria dorsalis pedis crosses the navicular; the former runs laterally under the extensor digitorum brevis; it supplies this and the tarsal articulations, anastomosing with branches of the arcuate, anterior lateral malleolar, lateral plantar and the perforating

branch of the peroneal. Two or three medial tarsal arteries ramify on the foot's medial border and join the medial malleolar network.

Arcuate artery (10.147). It arises near the medial cuneiform, passing laterally over the metatarsal bases, deep to the tendons of the digital extensors, and anastomosing with the lateral tarsal and plantar arteries. It supplies the *second to fourth dorsal metatarsal arteries*, running distally superficial to the corresponding dorsal interosseous muscles; in the interdigital clefts each divides into two *dorsal digital branches* for the adjoining toes. Proximally, in the interosseous spaces, they receive *proximal perforating branches* from the plantar arch and distally are joined by the *distal perforating branches* from the plantar metatarsal arteries. The fourth dorsal metatarsal sends a branch to the lateral side of the fifth toe.

First dorsal metatarsal artery (10.147). It arises just before the arteria dorsalis pedis enters the sole; it runs distally on the first dorsal interosseous; at the cleft between the first and second toes it divides, one branch passing under the tendon of extensor hallucis longus and supplying the medial side of the hallux and one bifurcating to supply the adjoining sides of hallux and the second toe.

POSTERIOR TIBIAL ARTERY

The posterior tibial artery begins at the distal border of the popliteus, between tibia and fibula, descending medially in the flexor compartment to divide midway between the medial malleolus and the medial tubercle of calcaneus, under abductor hallucis, into the medial and lateral plantar arteries (10.144, 145, 148).

Relations. The artery is successively **posterior** to tibialis posterior, flexor digitorum longus, tibia and ankle joint. Proximally, gastrocnemius, soleus and the deep transverse fascia of the leg are **superficial** and distally only the skin and fascia. It is parallel with and about 2.5 cm anterior to the medial border of the tendo calcaneus; terminally it is **deep** to the flexor retinaculum and abductor hallucis. It is accompanied by two veins and the tibial nerve, the latter first medial, but soon crossing posterior, and then largely posterolateral. The arrangement of structures passing from the leg to the sole is described on page 890.

Surface anatomy. The posterior tibial artery corresponds to a line joining a point 1–2 cm lateral to the calf's midline at the fibular neck's level, extending downwards and medially to the midpoint between the medial malleolus and the heel (medial calcaneal tubercle).

Branches. These are circumflex fibular, peroneal, nutrient, medial and lateral plantar.

Circumflex fibular artery. This artery, which sometimes arises from the anterior tibial artery, passes laterally round the fibula's neck through the soleus to anastomose with the lateral inferior genicular, medial genicular and anterior tibial recurrent arteries. It supplies bone and articular structures.

Peroneal artery (10.144, 148, 149). It arises about 2.5 cm distal to popliteus, and passes obliquely to the fibula, descending along its medial crest in a fibrous canal between tibialis posterior and flexor hallucis longus or in the latter. Reaching the inferior tibiofibular syndesmosis, it divides into the calcaneal branches, ramifying on the lateral and posterior surfaces of the calcaneus. **Proximally** it is covered by the soleus and deep transverse fascia, between this and the deep muscles; **distally** it is overlapped by flexor hallucis longus.

Variations. The artery may spring earlier from the posterior tibial, or even the popliteal, sometimes 7 or 8 cm **distal** to popliteus. It is more often enlarged and either joins and reinforces the posterior tibial artery or replaces it in the distal leg and foot.

Muscular branches. These supply soleus, tibialis posterior, flexor hallucis longus and peronei.

Nutrient artery. This runs proximally into the fibula.

Perforating branch. It traverses the interosseous membrane about 5 cm proximal to the lateral malleolus to enter the extensor compartment, where it anastomoses with the anterior lateral malleolar artery; descending anterior to the inferior tibiofibular syndesmosis, it supplies the tarsus, anastomosing with the lateral tarsal artery. This branch is sometimes enlarged and may replace the arteria dorsalis pedis. A *communicating branch* connects it about 5 cm proximal to the ankle to a *communicating branch* of the posterior tibial. The calcaneal or terminal branches anastomose with the anterior lateral malleolar and calcaneal branches of the posterior tibial artery.

Nutrient artery of the tibia. It arises from the posterior tibial near its origin; supplying a few muscular branches it descends into the bone immediately distal to the soleal line. It is one of the largest of the nutrient arteries.

Muscular branches. These are distributed to the soleus and deep flexors of the leg.

Communicating branch of the posterior tibia. This runs posteriorly across the tibia about 5 cm above its distal end, deep to flexor hallucis longus, to join a communicating branch of the peroneal.

Medial malleolar branches. These pass round the tibial malleolus to the medial malleolar network.

Calcaneal branches. They arise just proximal to the terminal division of the posterior tibial; they pierce the flexor retinaculum to supply the fat and skin behind the tendo calcaneus and in the heel and muscles on the tibial side of the sole; they anastomose with medial malleolar arteries and calcaneal branches of the peroneal.

Medial plantar artery (10.151A, B). It is the smaller terminal branch of the posterior tibial, which passes distally along the medial side of the foot with the medial plantar nerve lateral to it. At first deep to abductor hallucis, it runs distally between this and flexor digitorum brevis, supplying both. Near the first metatarsal base, its calibre, diminished by muscular branches, is further diminished by a superficial stem and it then passes to reach the medial border of the hallux where it anastomoses with a branch of the first plantar metatarsal artery (see below). Its superficial stem trifurcates and supplies three superficial digital branches accompanying the digital branches of the medial plantar nerve to join the first to third plantar metatarsal arteries.

Surface anatomy. The trunk of the artery begins midway between the medial malleolus and heel (medial calcaneal tubercle) extending towards the first interdigital cleft as far as the navicular bone.

Lateral plantar artery (10.151A, B). The larger terminal branch of the posterior tibial passes distally and laterally to the fifth metatarsal base, the lateral plantar nerve medial to it. (Note that the plantar nerves lie between the plantar arteries.) Turning medially, with the nerve's deep branch, to the interval between the first and second metatarsal bases, it unites with the arteria dorsalis pedis to complete the plantar arch. As it passes laterally, it is first between the calcaneus and abductor hallucis, then between flexor digitorum brevis and flexor accessorius; running distally to the fifth metatarsal base it passes between flexor digitorum brevis and abductor digiti minimi
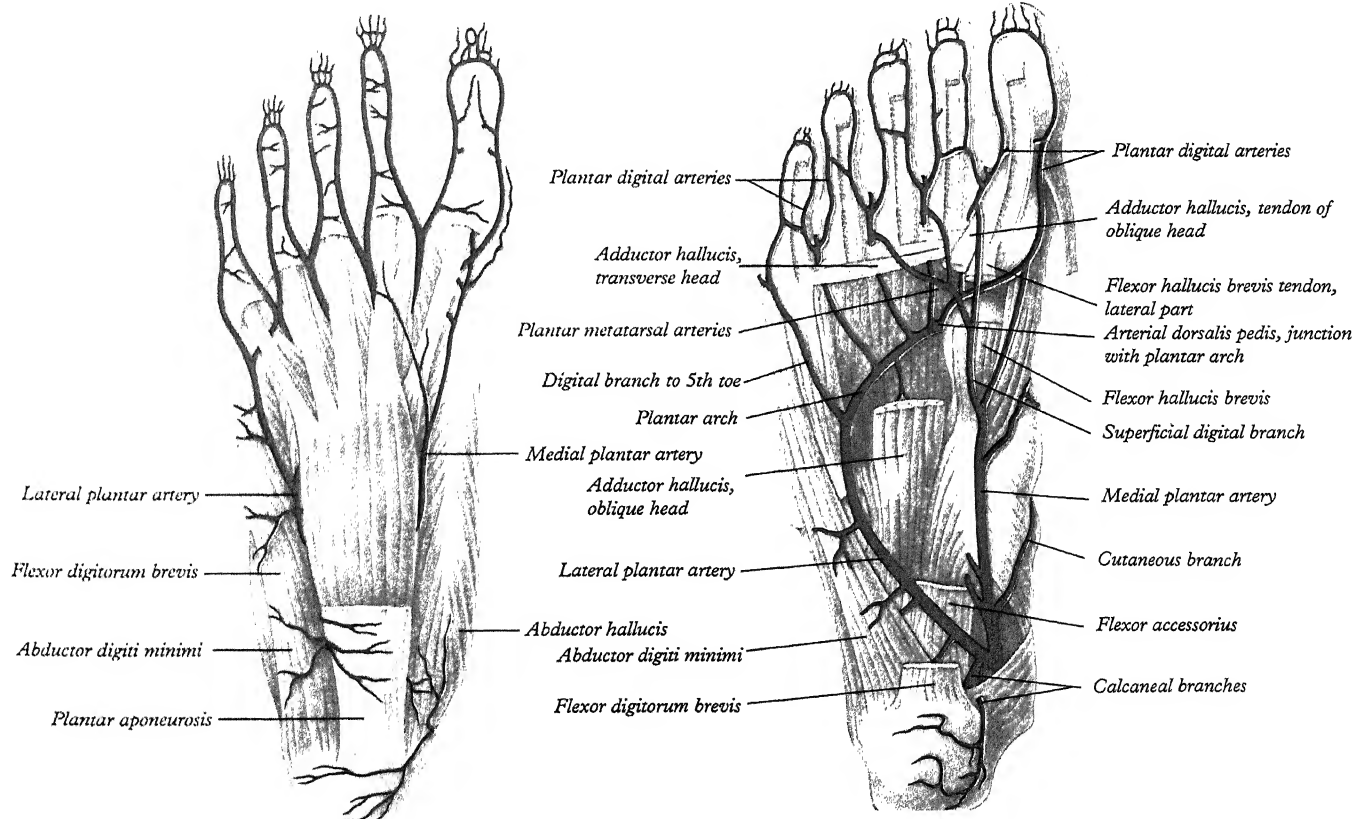
10.151A The plantar arteries of the right foot: superficial dissection.

10.151B The plantar arteries of the right foot: deep dissection.

and is covered by the plantar aponeurosis, superficial fascia and skin.

Branches. Muscular branches supply the adjoining muscles; *superficial branches* emerge along the lateral intermuscular septum to supply the skin and subcutaneous tissue lateral in the sole; *anastomotic branches* run to the lateral border, joining branches of the lateral tarsal and arcuate arteries. Sometimes a *calcaneal branch* pierces abductor hallucis to supply the skin of the heel.

PLANTAR ARCH

The plantar arch is deeply situated, extending from the fifth metatarsal base to the proximal end of the first interosseous space. Convex distally, it is plantar to the bases of the second to fourth metatarsal bones and corresponding interossei but dorsal to the oblique part of adductor hallucis.

Branches. Three perforating and four plantar metatarsal branches, and numerous branches supply the skin, fasciae and muscles in the sole. Three *perforating branches* ascend through the proximal ends of the second to fourth intermetatarsal spaces, between the heads of the dorsal interosseous muscles, anastomosing with the dorsal metatarsal arteries. Four *plantar metatarsal arteries* (10.151B) extend distally between the metatarsal bones in contact with the interossei. Each divides into two *plantar digital arteries*, supplying the adjacent digital aspects. Near its division each plantar metatarsal sends dorsally a *distal perforating branch* to join a dorsal metatarsal artery. The *first plantar metatarsal artery* springs from the junction between the lateral plantar and dorsalis pedis arteries, sending a digital branch to the medial side of the hallux. The lateral digital branch for the fifth toe arises directly from the lateral plantar artery near the fifth metatarsal base.

Surface anatomy. Beginning between the heel and medial malleolus, the lateral plantar artery crosses obliquely to a point 2.5 cm medial to the fifth metatarsal's tuberosity and with a slight distal convexity reaches the proximal end of the first intermetatarsal space.

Clinical anatomy. Haemorrhage from the plantar arch is difficult to stem, due to the depth of the vessel and its important close relations. It must be treated like the palmar arches (p. 1544).

PULSE

Palpating the pulse must surely be one of the most important aspects of the physical examination of a patient, giving information about both the state of the circulation and the rhythm of the heart. Prior to modern diagnostic techniques such as echocardiography and cardiac catheterization, feeling the pulse was (and still is in many circumstances) extremely helpful in diagnosing and assessing the state of diseased cardiac valves. The pulse is usually felt in the upper part of the body to assess the state of the circulation or cardiac output, and in the lower part of the body to evaluate the vascular tree with special reference to arteriosclerotic disease. The following are the commonly felt and most useful pulses in clinical practice.

Most of them are found where an artery is superficial and overlying bone.

Superficial temporal pulse (10.73). This pulse is of special value to anaesthetists as their access to patients is frequently restricted to the head. It is palpable anterior to the tragus of the ear as it crosses the zygomatic process of the temporal bone. The artery may be thickened and tender when involved by an arteritis.

Carotid pulse (10.75). This important pulse is palpable at the carotid bifurcation which usually lies at the level of the upper border of the thyroid cartilage just lateral to it. The pulse that one feels is formed by a complex of vessels: the common, internal and external carotid arteries plus the roots of the initial branches of the external carotid at that site. The carotid and femoral pulses are the ones usually sought in cases of suspected cardiac arrest.

Brachial pulse (10.98). Usually easily felt, it is in the cubital fossa lying medial to the tendon of biceps before disappearing under the bicipital aponeurosis. Many feel that this is the ideal site at which to assess the quality of the cardiac output. This is also a useful site at which to pass an arterial catheter for coronary angiography or cardiac catheterization.

Radial pulse (10.109). This is the most accessible pulse for palpation under normal clinical circumstances and it is usually of sufficient calibre to enable good quality information to be derived from it. Because of the palmar arches it is a safe site for cannulation for blood pressure monitoring and arterial blood sampling, as thrombosis there will not normally jeopardise the circulation of the hand. It is most easily felt on the ventral aspect of the wrist between the tendon of flexor carpi radialis and the lower lateral aspect of the radius.

Femoral pulse (10.140). Like the carotid pulse the femoral is of great value in assessing whether there is any significant cardiac output in cases of circulatory collapse. However, as with the other lower limb pulses, it may be reduced or obliterated by arteriosclerotic disease. It is a common site for coronary angiography and cardiac catheterization and is also a useful site for arterial puncture for blood gas analysis. It can usually be felt in the femoral triangle just below the inguinal ligament half way between the symphysis pubis and the anterior superior iliac spine.

Popliteal pulse (10.144). Lying deep in the popliteal fossa this is the most difficult of the peripheral pulses to feel. It is important, however, when assessing the state of the arterial supply to the lower limb especially in the presence of peripheral vascular disease, most commonly arteriosclerosis. The pulse is best felt with the knee flexed to relax the popliteal fascia when it may then be felt in the midline against the popliteal surface of the lower end of the femur.

Posterior tibial pulse (10.144). This may be felt behind and below the medial malleolus at the ankle between the tendons of flexor hallucis longus and flexor digitorum longus.

Dorsalis pedis pulse (10.147). Like the posterior tibial pulse, the dorsalis pedis may frequently be obliterated by peripheral vascular disease. It is normally palpable lateral to the tendon of extensor hallucis longus as it overlies the tarsal bones.

The veins as a whole form three main systems: pulmonary, systemic and portal. The *pulmonary veins* carry oxygenated blood from the lungs to the heart. The *systemic veins* return venous blood to the heart from much of the rest of the body. *Superficial veins* are located in the superficial fascia, especially in the limbs, and are variable in disposition. *Deep veins* lie beneath the deep fascia and are usually enclosed in connective tissue sheaths with accompanying arteries, the latter assisting venous return (p. 1468). Smaller arteries are accompanied by paired veins flanking them (*venae comitantes*); larger arteries are usually associated with single veins, although some run separately. Veins are usually more variable, in course and structure, than arteries. In many regions, such as the pelvis and vertebral column, veins form extensive plexuses devoid of valves. These plexuses are the basis of anastomosis between the veins of the trunk; they may also act as blood reservoirs of variable capacity. At many

points, such as the junctional regions between the trunk and limbs and near joints, valved *connecting veins* join superficial and deep systemic veins.

The *portal vein* receives tributaries draining venous blood from the subdiaphragmatic part of the oesophagus, the small intestine and the large intestine, the pancreas and the spleen; the blood from this vast area passes through the liver (hepatic circulation) before returning to a general systemic vein, the inferior vena cava.

The pulmonary veins return oxygenated blood to the left atrium. Usually four, two from each lung, and devoid of valves, they originate from capillary networks in the alveolar walls. By repeated

junctions tributary veins finally form a single trunk in each lobe, i.e. three in the right lung, and two in the left. The right middle and superior lobar veins usually join so that two veins, superior and inferior, leave each lung; they perforate the fibrous pericardium and open separately in the posterosuperior aspect of the left atrium (10.32, 39, 56B). Occasionally the three right lobar veins remain separate. Sometimes the two left pulmonary veins form a single trunk. Occasionally the two left pulmonary veins form a single trunk. Occasionally the two left pulmonary veins, each draining a lobe, may be augmented by an accessory lobar vein from each lobe and these may unite to form a third left pulmonary vein (Cory & Valentine 1959).

In the pulmonary hilum (pp. 1659, 1674) the superior pulmonary vein is antero-inferior to the pulmonary artery, the inferior being the most inferior hilar structure and also slightly posterior. The principle bronchus is posterior to the pulmonary artery. On the right the superior pulmonary vein passes posterior to the superior vena cava, the inferior behind the right atrium. On the left both pass anterior to the descending thoracic aorta. In the pericardium, they are partly covered by serous pericardium. Between the terminations of the right, and left veins is, centrally, the oblique pericardial sinus and, laterally, directed medially and upwards, smaller and variable pulmonary venous pericardial recesses (p. 1471).

In the following description the systemic veins are divided into six groups: cardiac veins, which drain directly into the heart; veins of the head and neck; veins of the upper limbs and veins of the thorax, all three groups draining into the superior vena cava; and veins of the lower limbs and veins of the abdomen and pelvis, both groups draining into the inferior vena cava.

Veins draining the heart can be grouped as:

the *coronary sinus* and *tributaries*, returning blood to the right atrium from the whole heart (including its septa) except the anterior region of the right ventricle and small, variable parts of both atria and left ventricle

the *anterior cardiac veins* draining an anterior region of the right ventricle and a region around the right cardiac border when the right marginal vein joins this group, ending principally in the right atrium

the *venae cordis minimae* (Thebesius' veins), opening into the right atrium and ventricle and, to a lesser extent, the left atrium and sometimes left ventricle.

CORONARY SINUS

The large majority of cardiac veins drain into the wide coronary sinus, about 2 or 3 cm long, lying posterior in the coronary sulcus (atrioventricular groove) between the left atrium and ventricle (10.32, 152). The sinus opens into the right atrium between the opening of the inferior vena cava and the right atrioventricular orifice, and its opening is guarded by an endocardial fold (*semilunar valve of the coronary sinus*; 10.33). Its tributaries are the great, small and middle cardiac veins, the posterior vein of the left ventricle and the oblique vein of the left atrium, all except the last having valves at their orifices.

Great cardiac vein (10.152). It begins at the cardiac apex, ascends in the anterior interventricular sulcus to the coronary sulcus and follows this to the left and round posterior to the heart to enter the coronary sinus at its origin. It receives tributaries from the left atrium and both ventricles, including the large *left marginal vein* ascending the left aspect ('obtuse border') of the heart.

Small cardiac vein (10.152). This lies posterior in the coronary

10.152 The principal veins of the heart.
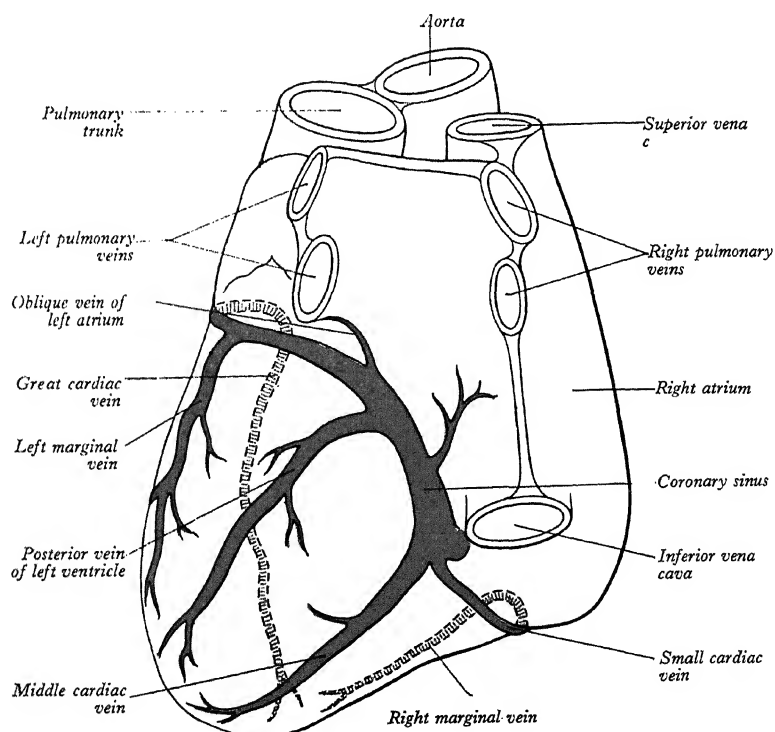
sulcus between the right atrium and ventricle and opens into the coronary sinus near its atrial end. It receives blood from the back of the right atrium and ventricle; the *right marginal vein* passes right, along the inferior cardiac margin ('acute border'), and may join the small cardiac vein in the coronary sulcus but more often opens directly into the right atrium.

Middle cardiac vein (10.152). Beginning at the cardiac apex, it runs back in the posterior interventricular groove to end in the coronary sinus near its atrial end.

Posterior vein of the left ventricle (10.152). Found on the diaphragmatic surface of the left ventricle a little left of the middle cardiac vein, it usually opens into the centre of the coronary sinus but sometimes into the great cardiac vein.

Oblique vein of the left atrium. This small vessel descends obliquely on the back of the left atrium to join the coronary sinus near its end; it is continuous above with the *ligament of the left vena cava* (p. 1472); the two structures are remnants of the left common cardinal vein.

ANTERIOR CARDIAC VEINS

The anterior cardiac veins drain the anterior part of the right ventricle. Usually two or three, sometimes even five (Baroldi & Scomazzoni 1967), they ascend in subepicardial tissue to cross the right part of the atrioventricular sulcus, passing deep or superficial to the right coronary artery. They end in the right atrium, near the sulcus, separately or in variable combinations. A subendocardial collecting channel, into which all may open, has been described (James 1961). The right marginal vein courses along the inferior ('acute') cardiac margin, draining adjacent parts of the right ventricle, and usually opens separately into the right atrium but may join the anterior cardiac veins or, less often, the coronary sinus. Because it is commonly independent it is often grouped with the venae cordis minimae but, since it is larger in calibre, it is comparable with the anterior cardiac veins or even wider. It is perhaps better considered one of the latter, which also sometimes drain with it into the coronary sinus. Mechanik (1934) described all cardiac veins as draining into the coronary sinus in the early fetal period.

VENAE CORDIS MINIMAE

The existence of venae cordis minimae, opening into all cardiac cavities, has been confirmed by many subsequent to their first recording by Thebesius (1708); they are more difficult to demonstrate than larger cardiac vessels. Their numbers and size are highly variable. Aho (1950) demonstrated 'minimal' veins of up to 2 mm in diameter opening into the right atrium and of about 0.5 mm into the right ventricle. He found venae minimae numerous in the right atrium and ventricle, occasional in and often absent from the left atrium, and rare in the left ventricle. Grant and Regnier (1926) considered venae minimae as derived from the intertrabecular spaces of the developing heart.

Cardiac venous anastomoses

There are widespread anastomoses at all levels of cardiac venous circulation, on a scale exceeding that of the arteries and amounting to a veritable venous plexus, according to some investigators (Baroldi & Scomazzoni 1967). Not only are adjacent veins often connected but connections also exist between tributaries of the coronary sinus and those of the anterior cardiac veins (Mierzwa & Kozielec 1975). Regions of abundant anastomoses are the apex and its anterior and posterior aspects. Like coronary arteries (p. 1505) cardiac veins connect with extracardiac vessels, chiefly the vasa vasorum of the large vessels continuous with the heart.

Variation in cardiac veins

Attempts to categorize variations in cardiac venous circulation (Aho 1950) into 'types' have not produced any accepted pattern. Major variations concern the general directions of drainage. The coronary sinus may receive all cardiac veins (except the venae minimae), including the anterior cardiac veins (33%), which may be reduced by diversion of some into the small cardiac vein and then to the coronary sinus (28%); the remainder (39%) represent the 'normal' pattern, as described above. Baroldi and Scomazzoni (1967) distinguished two major variants: a majority (70%) in which the small cardiac vein is independent, small or absent and a less frequent pattern (30%) in which this vein, though variable in size, connects with both coronary and anterior cardiac 'systems'.

The veins of the head and neck can be subdivided into three groups:

- veins of the exterior of the head and face
- cervical veins
- diploic, meningeal, intracranial veins and dural venous sinuses.

This classification is particularly significant at cranial level, where veins, like arteries, are arranged as a three-layered system:

- vessels of the scalp
- dural vessels
- cerebral and cerebellar vessels.

By comparison with the corresponding arteries, the veins of the scalp and dura are very variable and usually intercommunicate more extensively (emissary veins, p. 1589). Dural or meningeal arteries, on the other hand, are independent of cerebral and cerebellar arteries, the latter being derived from the internal carotid, whereas dural venous sinuses share a drainage to the internal jugular vein which is also common to veins of the cerebrum and cerebellum. The diploic veins constitute a hypothetical fourth venous tier; however, since these drain into dural veins, they are here grouped with them, following Browder and Kaplan (1976). It is to be noted that intracranial veins communicate at many points with extracranial vessels via the emissary and other veins (p. 1589).

Developmentally the venous sinuses emerge as venous plexuses; and it is clear, from angiographic studies and corrosion casts, that most sinuses preserve a plexiform arrangement to a variable degree, rather than being simple vessels with a single lumen. Browder and Kaplan (1976), examining human venous sinuses in hundreds of

corrosion casts, have observed vascular plexuses adjoining, in particular, the superior and inferior sagittal and straight sinuses and, with a lesser incidence, the transverse sinuses. Details show much individual variation; departures from 'average' patterns are frequent in earlier years; for example, the falx cerebelli may in infancy contain large plexiform channels and venous lacunae, augmenting the occipital sinus. Such variations cannot be detailed in a general text; in any case they must be established for the individual by angiography when clinical necessity arises; but the wide variation possible in the structure of cranial venous sinuses, with their plexiform nature and wide connections with cerebral and cerebellar veins, must be emphasized. Another kind of connection may be noted here; experiment shows (Rowbotham & Little 1962; Browder & Kaplan 1976) that parts of sinuses (and even diploic veins) can be filled by forcible internal carotid injection, suggesting the existence of arteriovenous shunts. Browder and Kaplan, by injection of the middle meningeal arteries, established a connection between these and the superior sagittal sinus at sites still unknown.

VEINS OF THE HEAD AND

As with most superficial veins these are subject to variations, far too numerous to illustrate. Some major features are, however, relatively constant; a common pattern is shown in (10.153).

Supratrochlear vein. This starts on the forehead from a venous network connected to the frontal tributaries of the superficial tem-
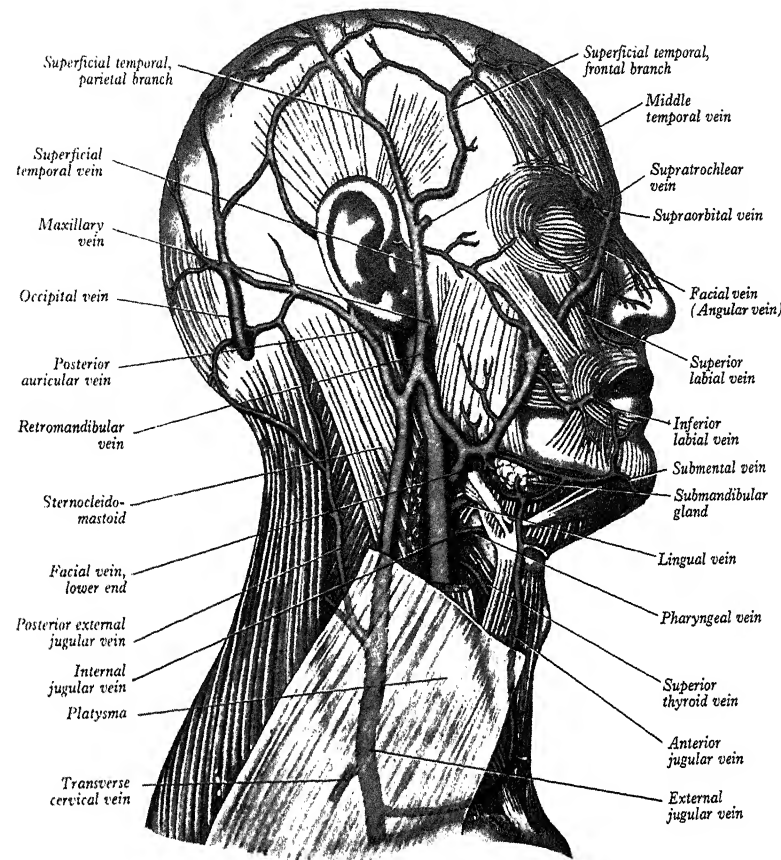
10.153 The veins of the right side of the head and neck. Parts of the right sternocleidomastoid and platysma have been excised to expose the trunk of the internal jugular vein. The external jugular vein is visible through the lower part of the platysma.

poral vein. Veins from this form a single trunk, descending near the midline parallel with its fellow to the radix nasi, across which they are joined by a nasal arch draining the dorsum nasi. The veins then diverge, each joining a supraorbital vein to form the facial vein near the medial canthus. Supratrochlear veins may join, dividing again on the radix nasi to form the two facial veins.

Supraorbital vein. It begins near the zygomatic process of the frontal bone, connecting with radicles of the superficial and middle temporal veins. Passing medially above the orbital opening under orbicularis oculi, it pierces this to form the facial vein by joining the supratrochlear near the medial canthus. A branch through the supraorbital notch joins the superior ophthalmic vein, receiving in the notch veins from the frontal sinus and frontal diploë.

Facial vein. After receiving the supratrochlear and supraorbital veins, this vessel descends obliquely near the side of the radix nasi, receding from the ala, and then turns posterolaterally below the orbital opening, passing downwards and backwards behind the facial artery, being less tortuous. It passes under zygomaticus major, risorius and platysma and then descends on to the anterior border and then the surface of the masseter, crosses the body of the mandible and runs obliquely back under the platysma but superficial to the submandibular gland, digastric and stylohyoid. A little antero-inferior to the mandibular angle it is joined by the anterior division of the retromandibular vein; descending superficial to the lingual artery's loop, the hypoglossal nerve and external and internal carotid arteries, it enters the internal jugular near the greater cornu of the hyoid bone (i.e. in the upper angle of the carotid triangle). Near its end a large branch often descends along the anterior border of sternocleidomastoid to the anterior jugular vein. Its uppermost segment, above its junction with the superior labial vein (see below), is often termed the *angular vein*.
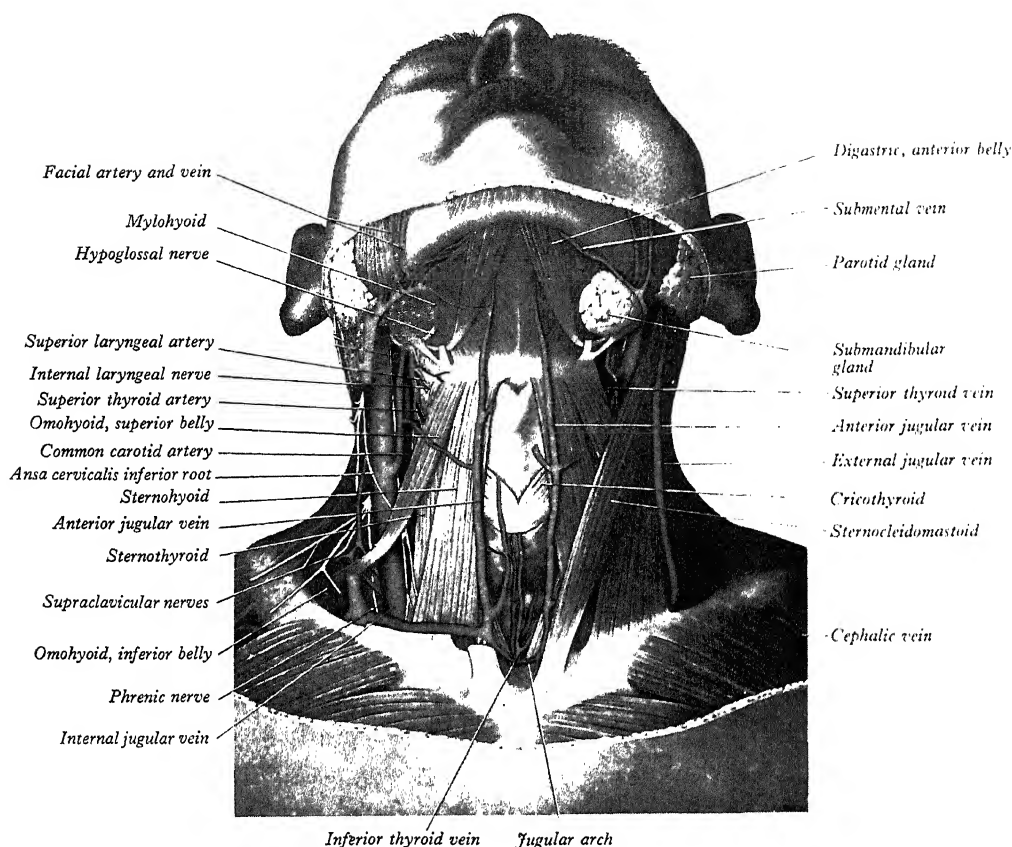
Tributaries. Near its beginning the facial vein connects with the superior ophthalmic directly and via the supraorbital; it is thus connected to the cavernous sinus. It receives veins of the ala nasi and, lower, a large deep facial vein from the pterygoid venous plexus and also the inferior palpebral, superior and inferior labial, buccinator, parotid and masseteric veins. Below the mandible, submental, tonsillar, external palatine (paratonsillar) and submandibular veins join it and sometimes the vena comitans of the hypoglossal nerve, and the pharyngeal and superior thyroid veins.

Clinical anatomy. The facial vein has no valves. It connects, as noted, with the cavernous sinus by two routes: through the ophthalmic vein or its supraorbital tributary, or by the *deep facial vein* to the pterygoid plexus and hence the cavernous sinus. Infection may thus spread from the face to the intracranial venous sinuses.

Superficial temporal vein (10.153). This begins in a widespread network joined across the scalp to the contralateral vein and to the ipsilateral supratrochlear, supraorbital, posterior auricular and occipital veins, all draining the same network. Anterior and posterior tributaries unite above the zygoma to form the superficial temporal, joined here by the *middle temporal vein*. It crosses the posterior root of the zygoma and enters the parotid gland to join the maxillary vein, to form the *retromandibular vein.*

Tributaries. These are the parotid veins, rami for the temporomandibular joint, anterior auricular veins, and transverse facial vein. The middle temporal vein, after receiving the orbital vein which is formed by the lateral palpebral veins, passes back between layers of temporal fascia, piercing this to join the superficial temporal vein.

Pterygoid venous plexus. It is found partly between temporalis and the lateral pterygoid, and partly between the pterygoids. Sphenopalatine, deep temporal, pterygoid, masseteric, buccal, dental, greater palatine and middle meningeal veins and a branch or branches from

1577

Facial artery and vein
Mylohyoid
Hypoglossal nerve

Superior laryngeal artery
Internal laryngeal nerve
Superior thyroid artery
Omohyoid, superior belly
Common carotid artery
Ansa cervicalis inferior root
Sternohyoid
Anterior jugular vein
Sternothyroid

Supraclavicular nerves

Omohyoid, inferior belly

Phrenic nerve

Internal jugular vein

Digastric, anterior belly
Submental vein
Parotid gland

Submandibular gland
Superior thyroid vein
Anterior jugular vein
External jugular vein
Cricothyroid
Sternocleidomastoid

Cephalic vein

Inferior thyroid vein   Jugular arch

10.154   Anterior view of the veins of the neck.

the inferior ophthalmic are all tributaries. The plexus connects by the *deep facial vein* with the facial and with the cavernous sinus through the sphenoidal emissary foramen, foramen ovale and foramen lacerum. Its deep temporal tributaries often connect with tributaries of the anterior diploic (p. 1580) and thus with the middle meningeal veins.

Maxillary vein. This short trunk accompanies the first part of the maxillary artery; it derives from the confluence of veins from the pterygoid plexus, passing back between the sphenomandibular ligament and mandibular neck, uniting with the superficial temporal to form the retromandibular vein.

Retromandibular vein. It descends in the parotid gland, between the external carotid artery and, superficially, the facial nerve. It divides into an anterior branch going forwards to join the facial and a posterior branch, joining the posterior auricular to form the *external jugular vein.* Occasionally it is not connected to the external jugular, which is then small, the anterior jugular often being enlarged.

Posterior auricular vein (10.153). Beginning in a parieto-occipital network, it also drains into tributaries of the occipital and superficial temporal veins. It descends behind the auricle to join the posterior division of the retromandibular vein in or just below the parotid gland, to form the external jugular. It receives a stylomastoid vein and tributaries from the cranial surface of the auricle.

Occipital vein (10.153). It begins in a posterior network in the scalp, pierces the cranial attachment of trapezius, turns into the suboccipital triangle and joins the deep cervical and vertebral veins. It may follow the occipital artery to end in the internal jugular; sometimes it joins the posterior auricular and hence the external jugular vein. Parietal and mastoid emissary veins link it with the superior sagittal and transverse sinuses. The occipital diploic vein sometimes joins it (see above).

VEINS OF THE NECK

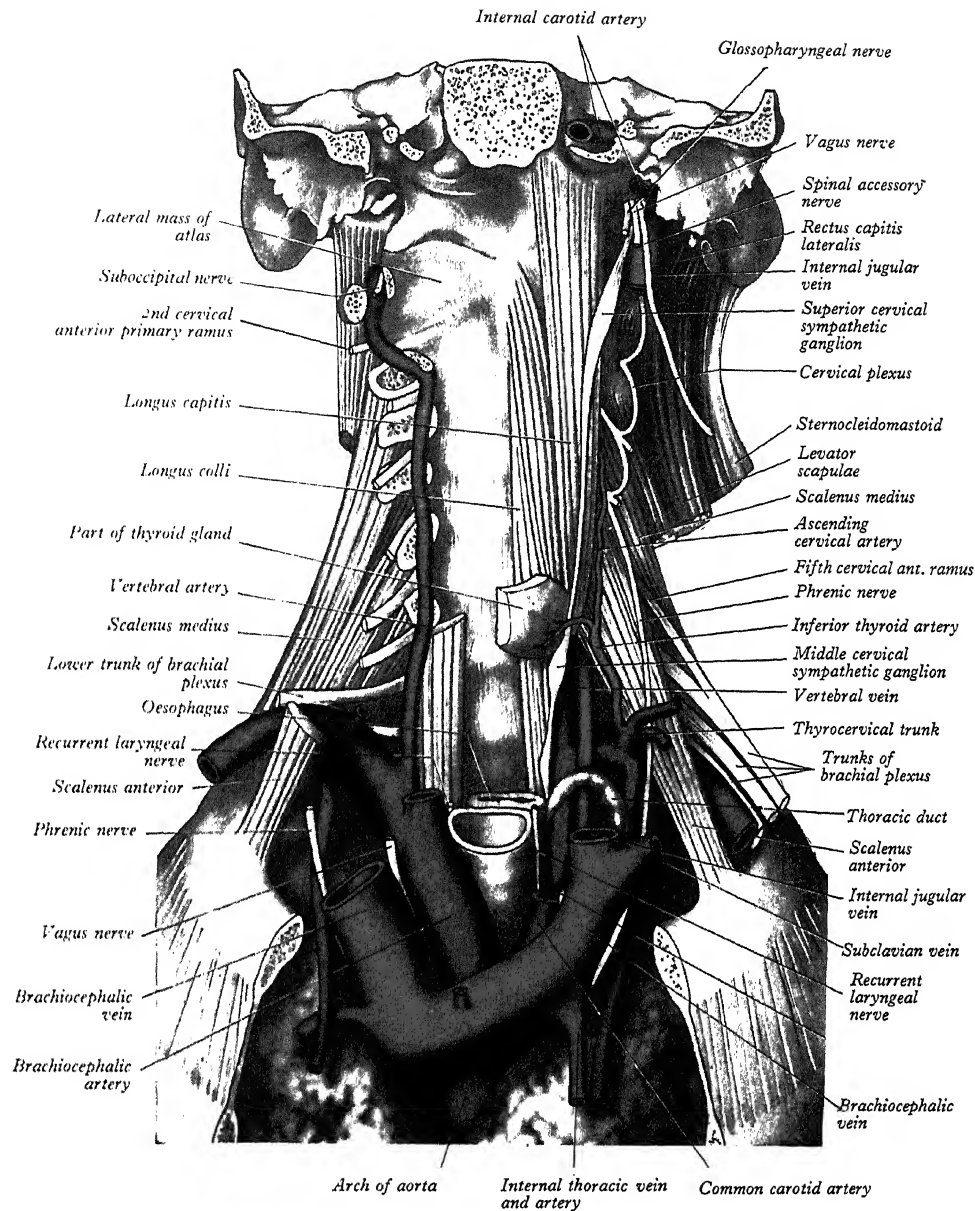1578   Veins of the neck are superficial or deep to the deep fascia but

they are not entirely separate (10.153, 154, 170). *Superficial veins,* tributaries (some with specific names, given below) of the external jugular, drain a much smaller volume of tissue than the *deep veins,* which drain all but the subcutaneous structures, mostly into the internal jugular vein (but some into the vertebral veins).

External jugular vein (10.153). This largely drains the scalp and face but also some deeper parts. The union of the posterior division of the retromandibular and posterior auricular veins begins near the mandibular angle just below or in the parotid gland, descending from the angle to the midclavicle. It crosses obliquely, superficial to sternocleidomastoid, to the subclavian triangle, where it traverses the deep fascia to end in the subclavian vein, lateral or anterior to scalenus anterior. Its wall is adherent to the rim of the fascial opening. It is covered by platysma, superficial fascia and skin, separated from sternocleidomastoid by deep cervical fascia; it crosses the transverse cervical nerve and is parallel with the great auricular nerve, ascending posterior to its upper half. In size the vein is inversely proportional to other veins in the neck; it is occasionally double. It has valves at its entrance into the subclavian vein and about 4 cm above the clavicle, between which it is often dilated, is a so-called sinus. The valves do not prevent regurgitation.

Tributaries. In addition to formative tributaries, the external jugular receives the posterior external jugular and, near its end, transverse cervical, suprascapular and anterior jugular veins; in the parotid gland it is often joined by a branch from the internal jugular. The occipital vein occasionally joins it.

Posterior external jugular vein. It begins in the occipital scalp and drains the skin and the superficial muscles posterosuperior in the neck. It usually joins the middle part of the external jugular.

Anterior jugular vein (10.153, 154). This vein starts near the hyoid bone by the confluence of the superficial submandibular veins. It descends between the midline and the anterior border of sternocleidomastoid; turning laterally, low in the neck, posterior (deep) to the muscle but superficial to the hyoid depressors, it joins the end of the external jugular vein or the subclavian vein directly. In size it is usually inverse to the external jugular. It communicates with the

Internal carotid artery

Glossopharyngeal nerve

Vagus nerve

Spinal accessory nerve

Rectus capitis lateralis

Internal jugular vein

Superior cervical sympathetic ganglion

Cervical plexus

Sternocleidomastoid

Levator scapulae

Scalenus medius

Ascending cervical artery

Fifth cervical ant. ramus

Phrenic nerve

Inferior thyroid artery

Middle cervical sympathetic ganglion

Vertebral vein

Thyrocervical trunk

Trunks of brachial plexus

Thoracic duct

Scalenus anterior

Internal jugular vein

Subclavian vein

Recurrent laryngeal nerve

Brachiocephalic vein

Lateral mass of atlas

Suboccipital nerve

2nd cervical anterior primary ramus

Longus capitis

Longus colli

Part of thyroid gland

Vertebral artery

Scalenus medius

Lower trunk of brachial plexus

Oesophagus

Recurrent laryngeal nerve

Scalenus anterior

Phrenic nerve

Vagus nerve

Brachiocephalic vein

Brachiocephalic artery

Arch of aorta   *Internal thoracic vein and artery*   *Common carotid artery*

10.155 A dissection to show the prevertebral region and the superior mediastinum. On the right the costal elements of the upper six cervical vertebrae have been removed to expose the cervical part of the vertebral artery. On the left most of the deep relations of the common carotid artery and the internal jugular vein are exposed. Details of the terminal parts of the left lymphatic trunks have been omitted.

internal jugular, receiving the laryngeal veins and sometimes a small thyroid vein. There are usually two anterior jugular veins, united just above the manubrium by a large transverse jugular arch, receiving the inferior thyroid tributaries. They have no valves and may be replaced by a midline trunk.

Surface anatomy. Usually the external jugular vein is visible where it crosses the sternocleidomastoid; it can be distended and made more visible by expiring against resistance (Valsalva's manoeuvre) or by gentle supraclavicular digital pressure. Similarly, the anterior jugular vein can often be made visible in the upper two-thirds of the neck. The end of the facial vein runs from a point where the anterior border of the masseter meets the inferior mandibular border, to the greater hyoid cornu.

Internal jugular vein (10.153, 154). This large vein collects blood from the skull, brain, superficial parts of face and much of the neck. It begins at the cranial base in the posterior compartment of the jugular foramen, continuous with the sigmoid sinus. At its origin is its *superior bulb*, which is below the posterior part of the tympanic floor. The vein descends in the carotid sheath (p. 804), uniting with

the subclavian, posterior to the sternal end of the clavicle, to form the brachiocephalic vein. It is also dilated near its end as its *inferior bulb*, above which it contains a pair of valves. **Posterior** to the vein, from above, are: the rectus capitis lateralis, transverse process of atlas, levator scapulae, scalenus medius and cervical plexus, scalenus anterior, phrenic nerve, thyrocervical trunk, vertebral vein and first part of subclavian artery; on the left it also crosses anterior to the thoracic duct (**10.155**). **Medial** to the vein are the internal and common carotid arteries and the vagus nerve between vein and arteries but posterior to them. **Superficially** the vein is overlapped above, then covered below by sternocleidomastoid and crossed by the posterior belly of the digastric and the superior belly of omohyoid. Superior to the digastric, the parotid gland and styloid process are superficial, the accessory nerve, posterior auricular and occipital arteries crossing the vein. Between the digastric and the omohyoid, the sternocleidomastoid arteries and inferior root of the ansa cervicalis cross it, but the nerve often passes between the vein and the common carotid. Below the omohyoid, it is covered by the infrahyoid muscles and the sternocleidomastoid and it is crossed by the anterior

15

jugular vein. Deep cervical lymph nodes lie along the vein, mainly on its superficial aspect. At the root of the neck the right internal jugular is separated from the common carotid, but the left usually overlaps its artery. At the base of the skull the internal carotid artery is **anterior**, separated from the vein by the *ninth* to *twelfth cranial nerves*.

Clinical anatomy. The vein is represented in surface projection by a broad band from the ear's lobule to the medial end of the clavicle; its inferior bulb is in the depression between the sternal and clavicular heads of the sternocleidomastoid, the lesser supraclavicular fossa, where a needle can be inserted with precision in the living subject.

Tributaries. These are: the inferior petrosal sinus, facial, lingual, pharyngeal, superior and middle thyroid veins, sometimes the occipital. The internal jugular vein may communicate with the external. The thoracic duct opens near the union of the left subclavian and internal jugular veins; the right lymphatic duct is at the same site on the right.

Inferior petrosal sinus. It leaves through the anterior part of the jugular foramen, crosses lateral or medial to the ninth to eleventh cranial nerves and joins the superior jugular bulb.

Lingual veins. These veins follow two routes:

- *Dorsal lingual veins* drain the dorsum and sides of the tongue and join the lingual veins accompanying the lingual artery between hyoglossus and genioglossus. Near the greater cornu of the hyoid bone they join the internal jugular.
- The *deep lingual vein* begins near the tip and runs back near the mucous membrane on the tongue's inferior surface. Near the anterior border of hyoglossus it joins a *sublingual vein*, from the salivary gland, to form the *vena comitans nervi hypoglossi* which runs back between the mylohyoid and hyoglossus with the hypoglossal nerve to join the facial, internal jugular or lingual vein.

Pharyngeal veins. These begin in a pharyngeal plexus external to the pharynx. After receiving meningeal veins and a vein from the pterygoid canal, they end in the internal jugular but sometimes in the facial, lingual or superior thyroid vein.

Superior thyroid vein (10.153,154). Formed by deep and superficial tributaries corresponding to the arterial branches, this vein accompanies the artery and receives the *superior laryngeal* and *cricothyroid veins*, ending in the internal jugular or facial vein.

Middle thyroid vein (10.154). It drains the lower part of the gland and also receives veins from the larynx and trachea. It crosses anterior to the common carotid artery to join the internal jugular vein behind the superior belly of omohyoid.

Facial and occipital veins. These are described on pages 1577–1578.

Inferior thyroid veins. See page 1592.

Vertebral vein. In the suboccipital triangle many small tributaries from internal vertebral plexuses leave the vertebral canal above the posterior atlantal arch and join small veins from local deep muscles making a vessel which enters the foramen in the atlantal transverse process and forms a plexus around the vertebral artery, descending through successive transverse foramina. This ends as the vertebral vein, emerging from the sixth cervical transverse foramen, whence it descends, at first anterior then anterolateral to the vertebral artery, to open superoposteriorly into the brachiocephalic vein; the opening has a paired valve. The vertebral vein descends behind the internal jugular, passing in front of the first part of the subclavian artery (10.155). A small accessory vertebral vein usually descends from the vertebral plexus, traverses the seventh cervical transverse foramen and turns forwards between the subclavian artery and the cervical pleura to join the brachiocephalic vein.

Tributaries. The vein connects with the sigmoid sinus by a vessel in the posterior condylar canal, when this exists. It also receives branches from the occipital vein, prevertebral muscles, internal and external vertebral plexuses. It is joined by anterior vertebral and deep cervical veins (see below) and sometimes near its end by the first intercostal vein.
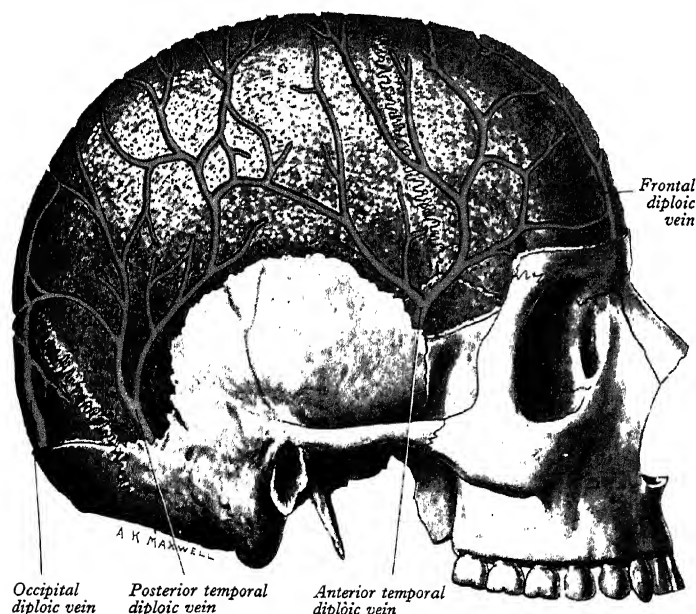
Anterior vertebral vein. Starting in a plexus around the upper cervical transverse processes, it descends near the ascending cervical artery between attachments of scalenus anterior and longus capitis and opens into the end of the vertebral vein.

Deep cervical vein. It accompanies its artery between the semispinales capitis et cervicis. It begins in the suboccipital region from communicating branches of the occipital and veins from suboccipital muscles and also from plexuses around the cervical spines. It passes forwards between the seventh cervical transverse process and the neck of the first rib to end in the lower part of the vertebral vein.

Clinical anatomy

When the superior jugular bulb thromboses (e.g. in otitis media), the glossopharyngeal, vagus and accessory nerves may be affected. The internal jugular vein may be endangered during removal of tuberculous or neoplastic lymph nodes.

Venous pulsation may be visible in the external jugular at the root of the neck. There are no valves in the brachiocephalic veins or the superior vena cava; hence the right atrial systole causes a wave of distension up these vessels, which may appear as a feeble flicker over the external jugular vein. This atrial systolic impulse is much increased when the right atrium is abnormally distended or hypertrophied, as in diseases of the mitral valve.

Frontal diploic vein

Occipital diploic vein   *Posterior temporal diploic vein*   *Anterior temporal diploic vein*

10.156 The veins of the diploë, displayed by the removal of the outer table of the skull.
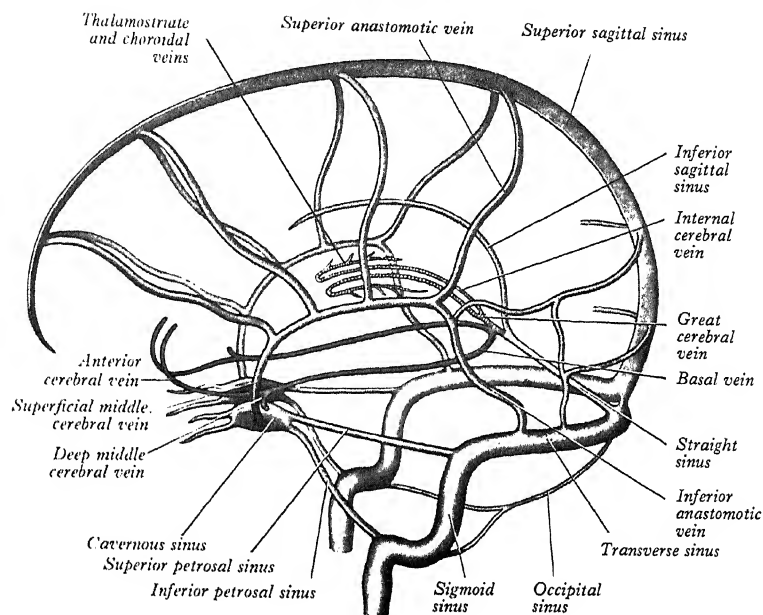
DIPLOIC VEINS

Diploic veins occupy channels in the diploë of some cranial bones (10.156) and are devoid of valves. They are large, with dilatations at irregular intervals; their thin walls are merely endothelium supported by elastic tissue. Radiographically they may appear as relatively transparent bands 3 or 4 mm wide. Absent at birth, they begin to develop with the diploë at about 2 years. They communicate with meningeal veins, dural sinuses and pericranial veins. Recognizably regular channels are:

- a *frontal diploic vein*, emerging from bone in the supraorbital foramen to join the supraorbital vein
- an *anterior temporal (parietal) diploic vein*, confined chiefly to the frontal bone, which pierces the greater wing of the sphenoid to end in the sphenoparietal sinus or anterior deep temporal vein
- a *posterior temporal (parietal) diploic vein*, in the parietal bones, descending to the parietal mastoid angle to join the transverse sinus through a foramen at the angle or mastoid foramen
- an *occipital diploic vein*, the largest, confined to the occipital bone, opening into occipital veins or the transverse sinus near the confluence of sinuses or into an occipital emissary vein.

Numerous small diploic veins emerge near the superior sagittal sinus to end in its venous lacunae (p. 1583).

Thalamostriate
and choroidal
veins

Superior anastomotic vein   Superior sagittal sinus

Inferior
sagittal
sinus

Internal
cerebral
vein

Great
cerebral
vein

Basal vein

Anterior
cerebral vein

Superficial middle.
cerebral vein

Deep middle
cerebral vein

Straight
sinus

Inferior
anastomotic
vein

Transverse sinus

Cavernous sinus
Superior petrosal sinus
Inferior petrosal sinus

Sigmoid
sinus

Occipital
sinus

10.157 Schema of the venous sinuses of the dura mater and their connections with the cerebral vein: left side. The more deeply placed cerebral veins are shown in blue and those inside the brain are shown in interrupted blue.

MENINGEAL VEINS

Meningeal veins begin from plexiform vessels in the dura mater and drain into efferent vessels in the outer dural layer which connect with lacunae of the superior sagittal sinus and with other cranial sinuses, including those accompanying the middle meningeal arteries (p. 1519), and with diploic veins.

CEREBRAL AND CEREBELLAR VEINS

The veins of the brain (p. 1220) have no valves; their thin walls have no muscular tissue. They pierce the arachnoid mater and the inner dural layer to open into the cranial venous sinuses. They comprise cerebral and cerebellar veins and veins of the brainstem.

The cerebral veins (10.157), external and internal, drain the surfaces and the interior of the hemispheres.

External cerebral veins (10.157)

The external cerebral veins form superior, middle and inferior groups.

Superior cerebral veins. Eight to twelve to each hemisphere, they drain their superolateral and medial surfaces and mainly follow the sulci, though some cross the gyri. Ascending to the superomedial border, they receive small veins from the medial surface and open into the superior sagittal sinus; anterior veins open almost at right angles; the larger, posterior veins are directed obliquely forwards against the current in the sinus. This may resist the collapse of thin-walled cerebral veins which might result from a rise of intracranial pressure; but another factor is the backward growth of the cerebral hemispheres and the consequent displacement of vessels during development.

Superficial middle cerebral vein. It begins on the lateral surface, following the posterior ramus and stem of the lateral sulcus to end in the cavernous sinus. A superior anastomotic vein runs posterosuperiorly between the middle cerebral vein and the superior sagittal sinus, thus connecting the superior sagittal and cavernous sinuses. An inferior anastomotic vein courses over the temporal lobe, connecting the middle cerebral vein to the transverse sinus.

Inferior cerebral veins. Those on the frontal orbital surface join the superior cerebral veins and thus drain to the superior sagittal sinus; those on the temporal lobe anastomose with basal and middle cerebral veins, draining to the cavernous, superior petrosal and transverse sinuses.

Basal vein. It begins at the anterior perforated substance by the union of:

- a small *anterior cerebral vein*, accompanying the anterior cerebral artery
- a *deep middle cerebral vein* receiving tributaries from the insula and neighbouring gyri and running in the lateral cerebral sulcus
- *striate veins* emerging from the anterior perforated substance.

The basal vein passes back round the cerebral peduncle to the great cerebral vein (10.157), receiving tributaries from the interpeduncular fossa, inferior cornu of the lateral ventricle, parahippocampal gyrus and midbrain.

Internal cerebral vein (10.157)

The internal cerebral vein is formed near the interventricular foramen primarily by the thalamostriate and choroid veins; it drains the deep parts of its hemisphere. Numerous smaller veins from surrounding structures also converge here; each runs back parallel to its fellow between the layers of the tela choroidea of the third ventricle and below the splenium, where they join to form the median great cerebral vein.

Thalamostriate vein. Running anteriorly between the caudate nucleus and thalamus, this vein receives many veins from both and unites behind the anterior column of the fornix with the choroid vein to form the internal cerebral.

Choroid vein. This runs along (curves or 'spirals' along) the whole choroid plexus, receiving veins from the hippocampus, fornix, corpus callosum and adjacent structures.

Great cerebral vein

The great cerebral vein starts by union of the two internal cerebral veins as a short median vessel curving sharply up around the splenium to open into the anterior end of the straight sinus, after receiving the right and left basal veins.

Cerebellar veins

The cerebellar veins course on the cerebellar surface, and comprise superior and inferior sets.

Superior cerebellar veins. Some run anteromedially across the superior vermis to the straight sinus or great cerebral vein; others run laterally to the transverse and superior petrosal sinuses.

Inferior cerebellar veins. They include a small median vessel running backwards on the inferior vermis to enter the straight or (either) sigmoid sinus; laterally coursing vessels join the inferior petrosal and occipital sinuses.

158
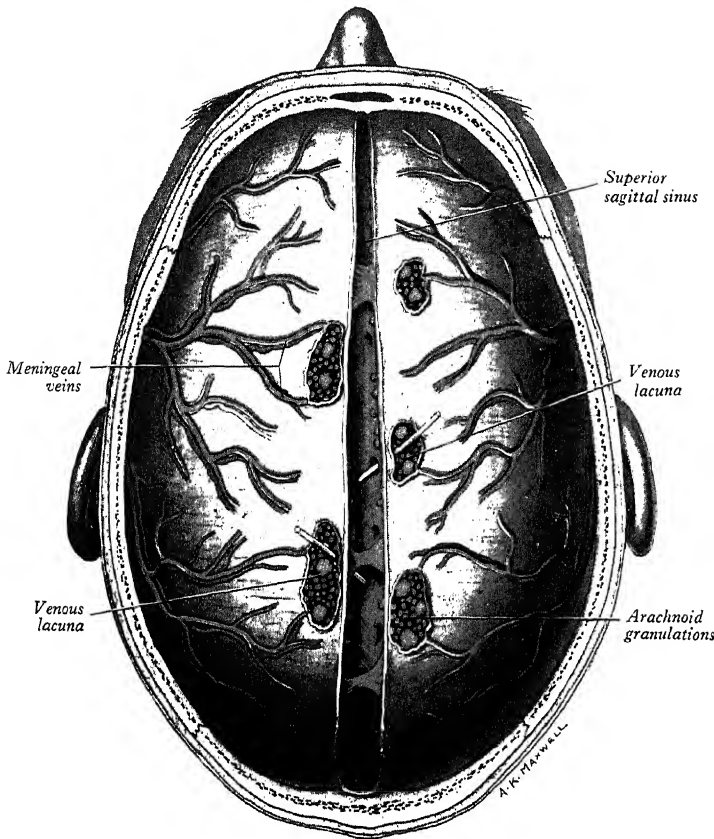
10.158 The superior sagittal sinus laid open after removal of the cranial vault. Some of the fibrous bands which cross the sinus are clearly seen; from two of the venous lacunae, bristles are passed into the sinus.

Veins of the brainstem

The veins of the brainstem form a superficial venous plexus deep to the arteries. Veins of the midbrain may reach the great cerebral or basal vein. Over the pons they tend to form a lateral vein on each side which, with upper medullary veins, may enter the petrosal sinuses, transverse sinus, cerebellar veins or the venous plexus of the (sphenoidal) foramen ovale. A median pontine vein may exist and join one of the basal veins. Veins of the inferior medulla oblongata communicate with spinal veins and drain into the adjacent venous sinuses or along variable radicular veins following the last four cranial nerves to the inferior petrosal or occipital sinuses or the upper part of the internal jugular vein. Anterior and posterior median medullary veins may run along the anterior medial fissure or posterior median sulcus and are then continuous with the spinal veins in corresponding positions (p. 1220).

## CRANIAL DURAL VENOUS SINUSES

Dural sinuses are venous channels, draining blood from the brain and cranial bones, and lying between two layers of dura mater. They are lined by endothelium, they have no valves, and their wall is devoid of muscular tissue. Although most accounts describe sinuses as largely simple, smooth channels, a complex 'cavernous' or plexiform nature has been emphasized by Browder and Kaplan (1976), at least in some sites (p. 1585). They may be divided into:

- a posterosuperior group
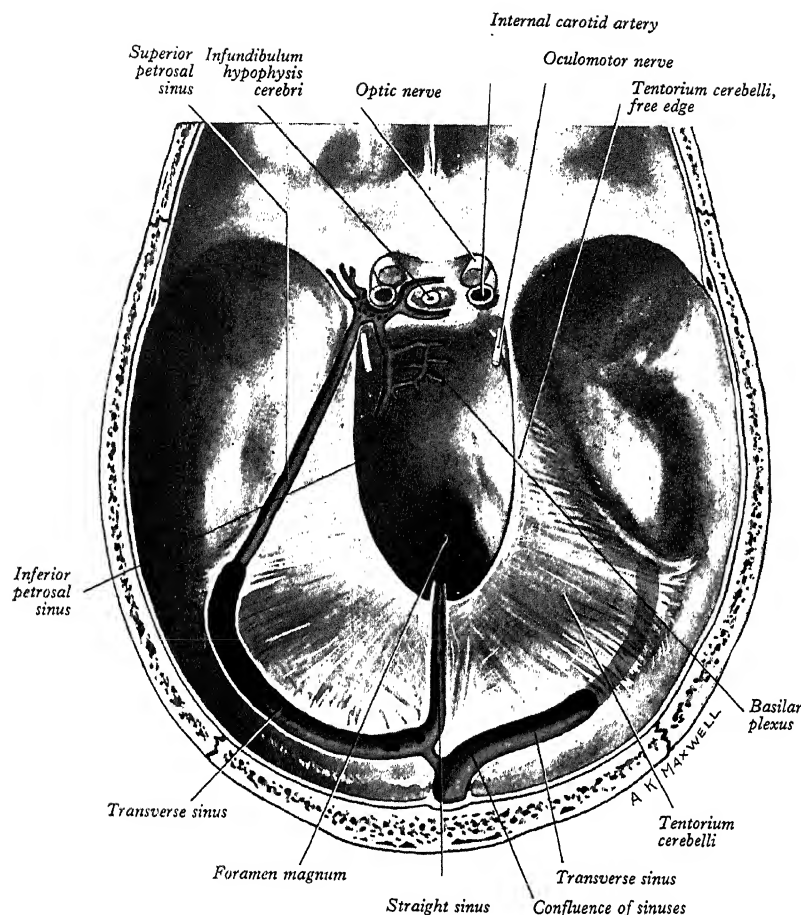- an antero-inferior group on the cranial base.

Posterosuperior group of venous sinuses

The posterosuperior group comprises the superior and inferior sagittal, straight, transverse, petrosquamous, sigmoid and occipital sinuses.

Superior sagittal sinus (10.157–159). It runs in the attached, convex margin of the falx cerebri. It is said to begin near the crista galli by receiving a vein from the nasal cavity when the foramen caecum is patent; but Kaplan et al (1973) found no such tributary in 201 specimens; in only 9% did the sinus extend as far as the
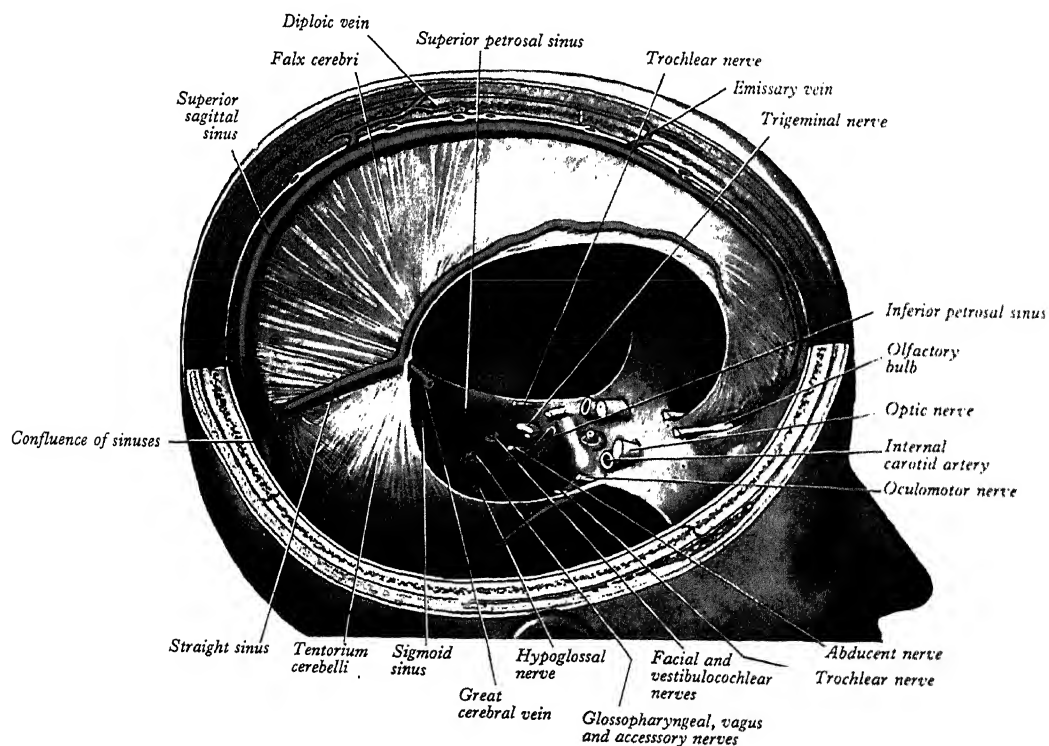
10.159 The dura mater, its processes and venous sinuses: right aspect. The cavernous and sphenoparietal sinuses are not represented.

Internal carotid artery

Superior *Infundibulum*
petrosal *hypophysis* *Oculomotor nerve*
sinus *cerebri* *Optic nerve* *Tentorium cerebelli,*
free edge

Inferior
petrosal
sinus

Basilar
plexus

Transverse sinus

Tentorium
cerebelli

Foramen magnum

Transverse sinus

Straight sinus *Confluence of sinuses*

10.160 The tentorium cerebelli and venous sinuses: superior aspect. Representation of the cavernous sinuses (or 'plexuses', see text) and their extensions is greatly simplified.

foramen; the first tributaries were cortical veins from the frontal lobes, the *ascending frontal veins* of Krayenbühl (1967). The sinus usually begins a few millimetres posterior to the foramen caecum and runs back, grooving the internal surface of the frontal bone, the adjacent margins of the two parietal bones and the squamous occipital bone. Near the internal occipital protuberance it deviates, usually to the right, continuing as a transverse sinus. Triangular in cross-section, it gradually enlarges backwards. Its interior shows the openings of superior cerebral veins, projecting arachnoid granulations, and many fibrous bands across its inferior angle; it also communicates by small orifices with irregular *venous lacunae*, situated in the dura mater near the sinus, usually three on each side: a small frontal, a large parietal and an occipital intermediate in size. In the elderly, lacunae tend to become confluent as one elongated lacuna on each side. Fine fibrous bands cross them and numerous arachnoid granulations project into them. The superior sagittal sinus receives the superior cerebral veins and, near the posterior end of the sagittal suture, veins from the pericranium passing through the parietal foramina; the lacunae drain the diploic and meningeal veins.

The complexity of these lateral lacunae and of the sinus itself has been obscured by over-simplification in general texts; but this complexity has often been emphasized (Clark 1920; Baló 1950) and studies of corrosion casts (Browder & Kaplan 1976) and cerebral angiography have revived earlier descriptions. Lateral lacunae are often so complex as to be almost plexiform and rarely the simple venous spaces usually depicted. All more recent observers have described plexiform arrays of small veins adjoining the sagittal, transverse and straight sinuses. Clark and Baló regarded these masses as cavernous tissue, which commonly adjoin all sinuses intercommunicating at their confluence. Ridges of such 'spongy' venous tissue often project into the lumina of the superior sagittal

and transverse sinuses. Their function can only be conjectured (p. 1214). The superior sagittal sinus is also invaded, in its intermediate third, by variable bands and projections from its dural walls, even extending as horizontal shelves dividing its lumen into superior and inferior channels. Such variable features make it impossible to give a simple description of this or other venous sinuses, whose variations have been detailed by Browder and Kaplan (1976) in a large series of corrosion casts; individual variations can only be shown by angiography.

Confluence of the sinuses (10.160). This term refers to the dilated posterior end of the superior sagittal sinus, situated to one side (usually right) of the internal occipital protuberance, where it turns to become a transverse sinus. It also connects with the occipital and contralateral transverse sinus. The size and degree of communication of the channels meeting at the confluence are variable (Browder & Kaplan 1976). In more than half of the specimens all venous channels converging towards the occiput do interconnect, including straight and occipital sinuses. In many instances, however, communication is absent or tenuous. Any sinus involved may be duplicated, narrowed or widened near the confluence. Variation is too great for useful description.

Clinical anatomy. Connections between the superior sagittal sinus and veins of the nose, scalp and diploë explain the occasional spread of infective thrombosis in these parts.

Inferior sagittal sinus. Located in the posterior half or two-thirds of the free margin of the falx cerebri, it increases in size posteriorly, ending in the straight sinus. It receives veins from the falx and sometimes from the medial cerebral surfaces.

Straight sinus (10.159, 160, 161). It lies in the junction of the falx cerebri with the tentorium cerebelli. Triangular in cross-section, it has a few transverse bands. It runs **postero-inferiorly**, continuing the

1583
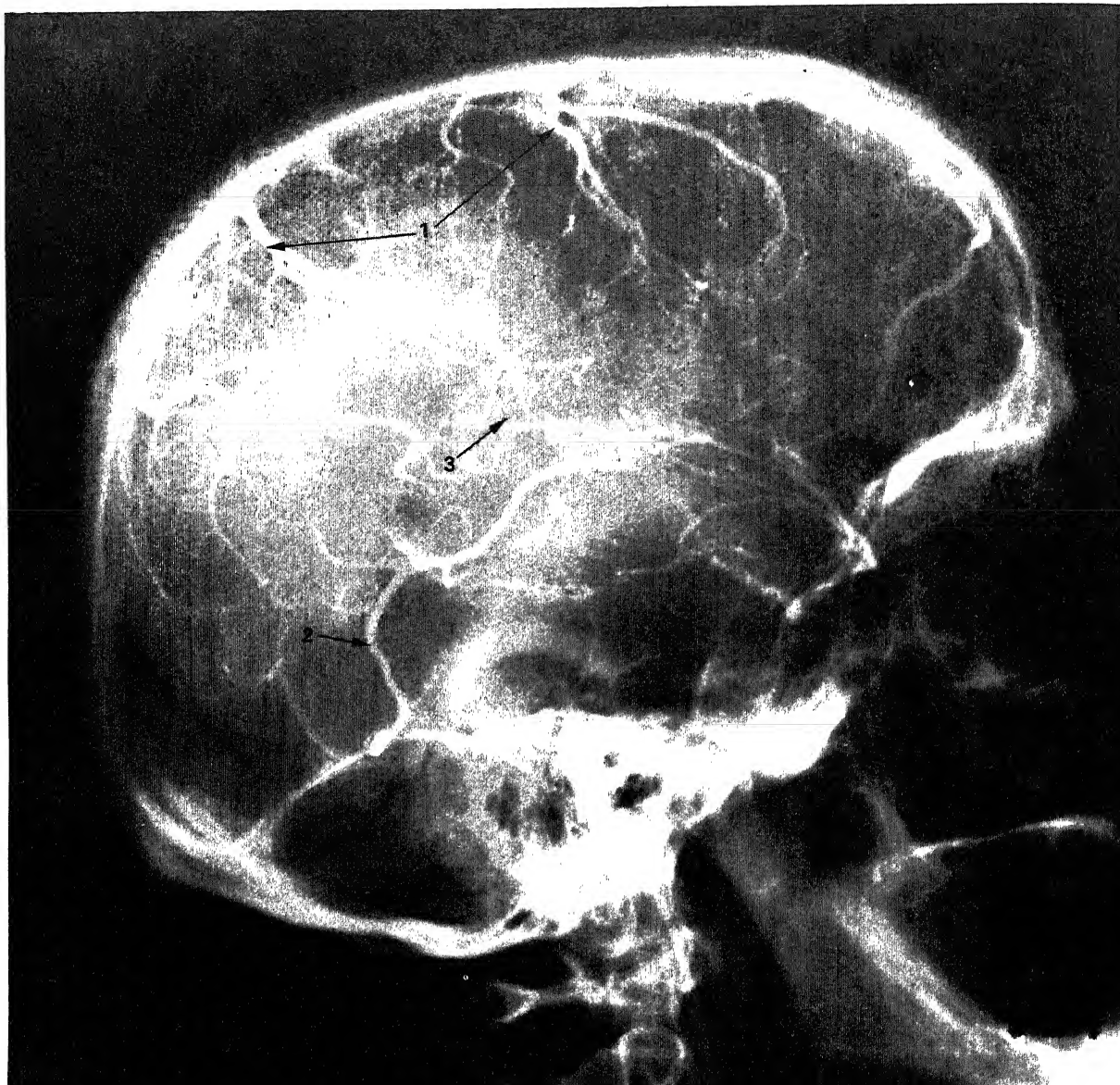
10.161 Internal carotid arteriogram (right), venous phase: lateral view. (Same subject as in 10.81 and 10.82, pp. 1522, 1524.) 1. Superior cerebral veins. Note the anterior course at entry into the superior sagittal sinus. 2. An inferior cerebral vein ending in the straight sinus. 3. Region of venous anastomoses.

inferior sagittal sinus into that transverse sinus which is not, or only tenuously, continuous with the superior sagittal sinus. It may communicate terminally, but quite variably, at the confluence. Its tributaries include some superior cerebellar veins and the great cerebral; the site of the latter's opening is marked by a dilatation. A small body projects into the floor of the sinus at its junction with the great cerebral vein. This contains a sinusoidal plexus of vessels; it may become engorged and act as a valve controlling outflow from the great cerebral vein, affecting the secretion of cerebrospinal fluid in the lateral ventricles. As noted, other masses of cavernous tissue are related to other dural sinuses; engorgement possibly influences their blood flow but structural data make this unlikely (see above).
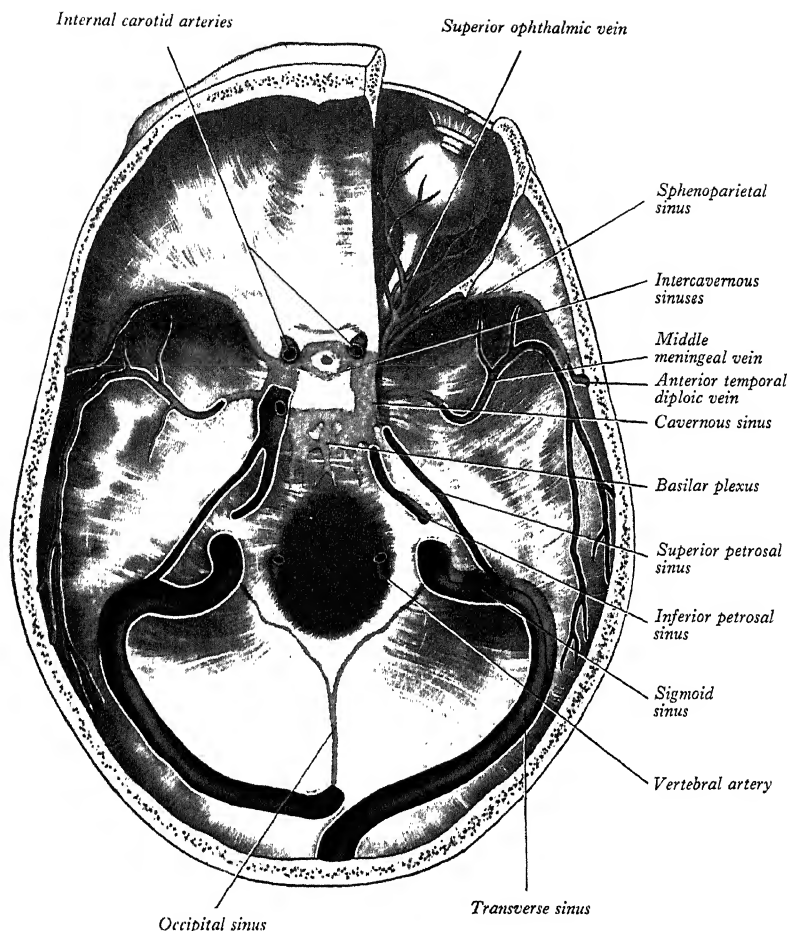
Transverse sinuses (10.160, 162). They begin at the internal occipital protuberance, one (right) directly continuous with the superior sagittal sinus, the other with the straight sinus. Each curves anterolaterally to the posterolateral part of the petrous temporal bone, where it turns down as a sigmoid sinus. It is in the attached margin of the tentorium cerebelli, first on the occipital's squama, then on the parietal's mastoid angle. It has a gentle curve, convex upwards, and increases in size as it proceeds forwards. Transverse sinuses are triangular in section and usually unequal in size, the one

draining the superior sagittal sinus being the larger. Where they continue as sigmoid sinuses, they are joined by the superior petrosal sinuses; they receive the inferior cerebral, inferior cerebellar, diploic and inferior anastomotic veins (p. 1581).

Petrosquamous sinus. It runs back in a groove, which sometimes becomes a canal posteriorly, along the junction of the squamous and petrous parts of the temporal bone, opening behind into the transverse sinus. Anteriorly it connects with the retromandibular vein through a postglenoid or squamous foramen (pp. 589, 590). The sinus may be absent; it may drain entirely into the retromandibular vein.

Sigmoid sinuses (10.162, 163). They are continuations of the transverse sinuses, beginning where these leave the tentorium cerebelli. Each sigmoid sinus curves inferomedially in a groove on the mastoid temporal bone, crosses the occipital's jugular process and turns forwards to the superior jugular bulb, lying posterior in the jugular foramen. Anteriorly, a thin plate of bone alone separates its upper part from the mastoid antrum and air cells. It connects with pericranial veins via mastoid and condylar emissary veins.

Occipital sinus (10.162). The smallest of the sinuses, it lies in the attached margin of the falx cerebelli, occasionally paired. It commences near the foramen magnum in several small channels, one

Labels on figure:
Internal carotid arteries
Superior ophthalmic vein
Sphenoparietal sinus
Intercavernous sinuses
Middle meningeal vein
Anterior temporal diploic vein
Cavernous sinus
Basilar plexus
Superior petrosal sinus
Inferior petrosal sinus
Sigmoid sinus
Vertebral artery
Occipital sinus
Transverse sinus

10.162 The sinuses at the base of the skull. The sinuses coloured dark blue have been opened up. See text and **10.165, 166** for alternative views on the construction of the cavernous sinuses.

joining the end of the sigmoid sinus; it connects with the internal vertebral plexuses and ends in the confluence of sinuses.

Antero-inferior group of venous sinuses

The antero-inferior group includes: cavernous, intercavernous, inferior petrosal, sphenoparietal, superior petrosal and basilar sinuses and middle meningeal 'veins'.

Cavernous sinuses (10.158, 163–166). They lie on the sides of the body of the sphenoid bone; their name refers to their internal structure. It has been asserted that a distended adult sinus contains a few trabeculae, mostly in its periphery near the entry of its tributaries, and that these are incorporations of plexiform tributaries during developmental expansion. When the sinus is collapsed, as is usual in cadavers, its cavity is encroached upon by the nerves and arachnoid granulations in its wall, creating a spurious resemblance to cavernous tissue (Butler 1957). From corrosion casts, however, Parkinson (1973) concluded that the sinus is usually a plexus (as it is during development), a finding in accord with some earlier descriptions; Pernkopf (1963) depicted the 'sinus' as a venous plexus (see **10.165, 166**). Browder and Kaplan (1976), from examination of many casts prepared in cadavers, described the sinus as 'reticulated'. It is not clear whether they meant plexiform or cavernous. The sinus extends from the superior orbital fissure to the apex of the petrous temporal bone, with an average length of 2 cm and width of 1 cm. The internal carotid artery, with a sympathetic plexus, passes forwards through the sinus, as does the abducent nerve, inferolateral to the artery; the oculomotor and trochlear nerves and ophthalmic and maxillary divisions of the trigeminal (**10.164**) are usually said to be in the thickness of its lateral wall; but they are of such diameters that they project into the sinus; while they may be surrounded by

dural connective tissue, they are usually covered medially by little more than endothelium (McGrath 1977). The sphenoidal air sinus and hypophysis cerebri are medial; the trigeminal cave is near the inferoposterior part of its lateral wall, extending posteriorly beyond it and enclosing the trigeminal ganglion. The uncus is also lateral.

Tributaries. These are: the superior ophthalmic vein, a branch from the inferior ophthalmic vein (or the whole vessel), the superficial middle cerebral vein, inferior cerebral veins and sphenoparietal sinus; the central retinal vein and frontal tributary of the middle meningeal sometimes drain to it. The sinus drains to the transverse sinus via the superior petrosal sinus, to the internal jugular via the inferior petrosal sinus and a plexus of veins on the internal carotid, to the pterygoid plexus by veins traversing the emissary sphenoidal foramen, foramen ovale and foramen lacerum and to the facial vein via the superior ophthalmic. The two sinuses are connected by anterior and posterior intercavernous sinuses and the basilar plexus. All connections are valveless; the direction of flow in them is reversible.

Propulsion of blood in the sinus is partly due to pulsation of the internal carotid artery. It is also influenced by gravity and hence by the position of the head.

Clinical anatomy. An arteriovenous leak may occur between the cavernous sinus and internal carotid artery, causing a pulsating orbital swelling. Ligation of the internal or common carotid artery has sometimes alleviated the condition. Suppuration in the upper nasal cavities and paranasal sinuses or near the medial canthus may lead to septic thrombosis of the cavernous sinuses.

Ophthalmic veins (10.163, 167). There is a superior and an inferior, devoid of valves, linking the facial and intracranial veins. The *superior ophthalmic vein* forms posteromedial to the upper
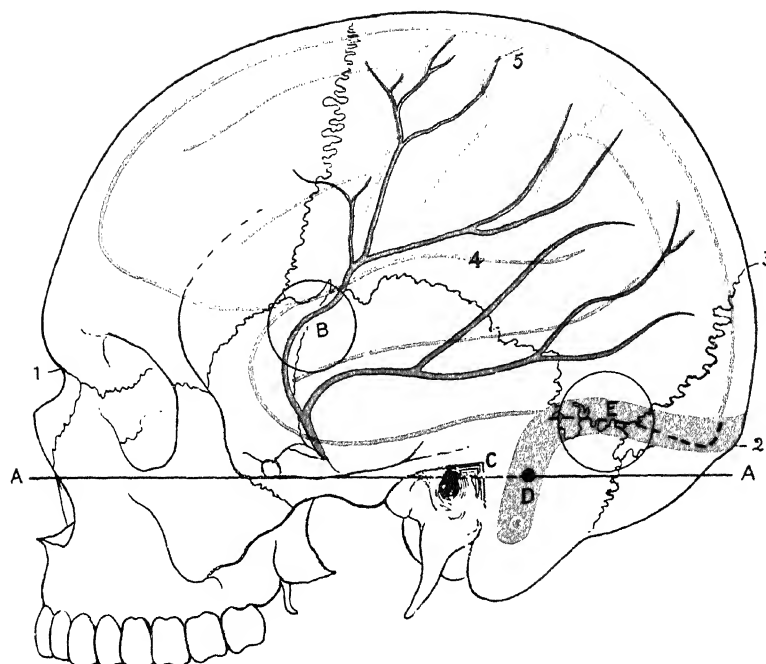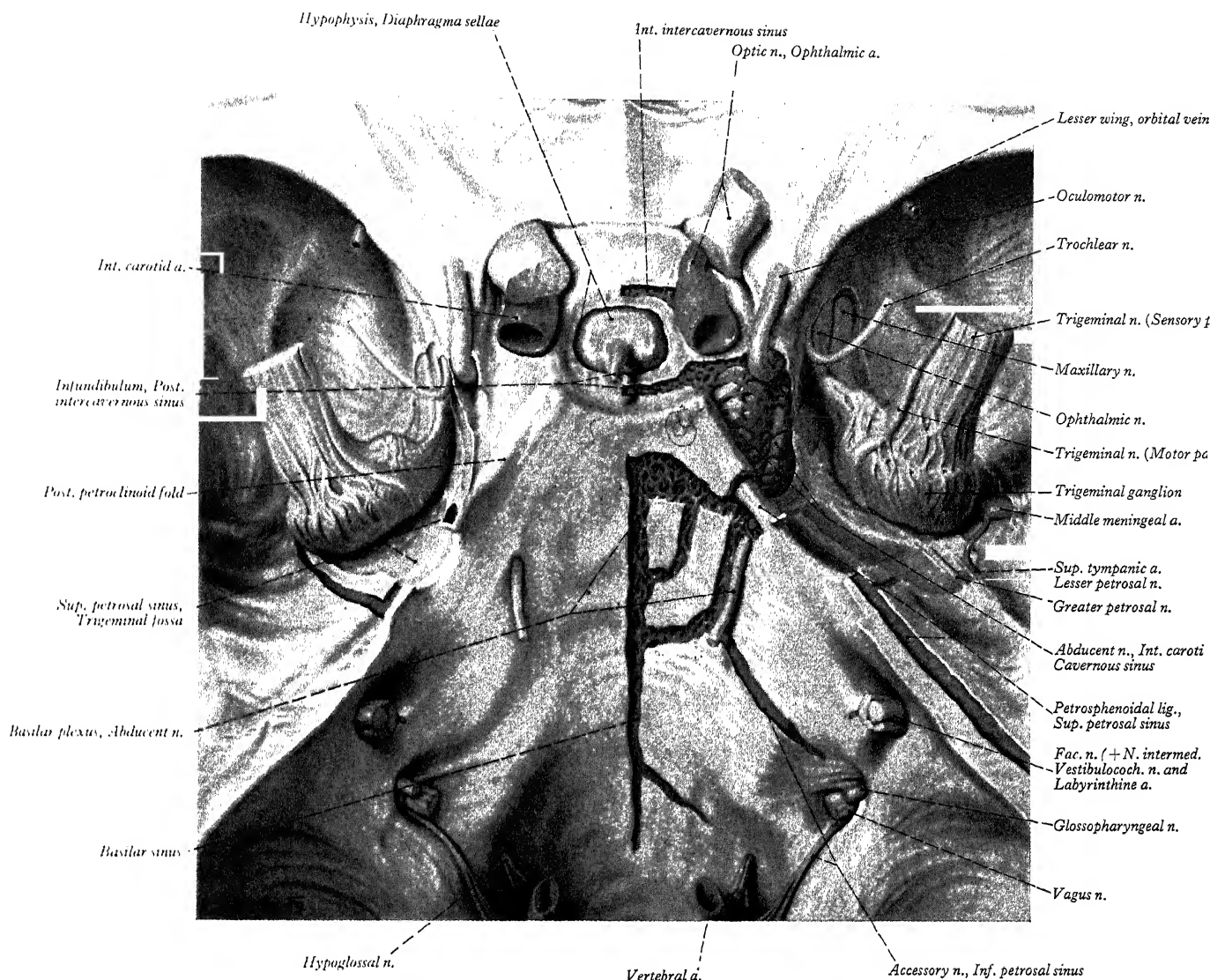
10.163 The relations of the brain, the middle meningeal artery and the transverse and sigmoid sinuses to the surface of the skull. 1. Nasion. 2. Inion. 3. Lambda. 4. Lateral cerebral sulcus. 5. Central sulcus. AA = Frankfurt plane, which traverses the lower margin of the orbital opening and the upper margin of the external acoustic meatus; B = area (including the pterion) for trephining over the frontal branch of the middle meningeal artery and the cerebral Sylvian point; C = suprameatal triangle; D = sigmoid sinus; E = area for trephining over the transverse sinus, exposing the dura mater of both cerebrum and cerebellum. The outline of the cerebral hemisphere and its major sulci are indicated in blue; the course of the middle meningeal artery is in red.
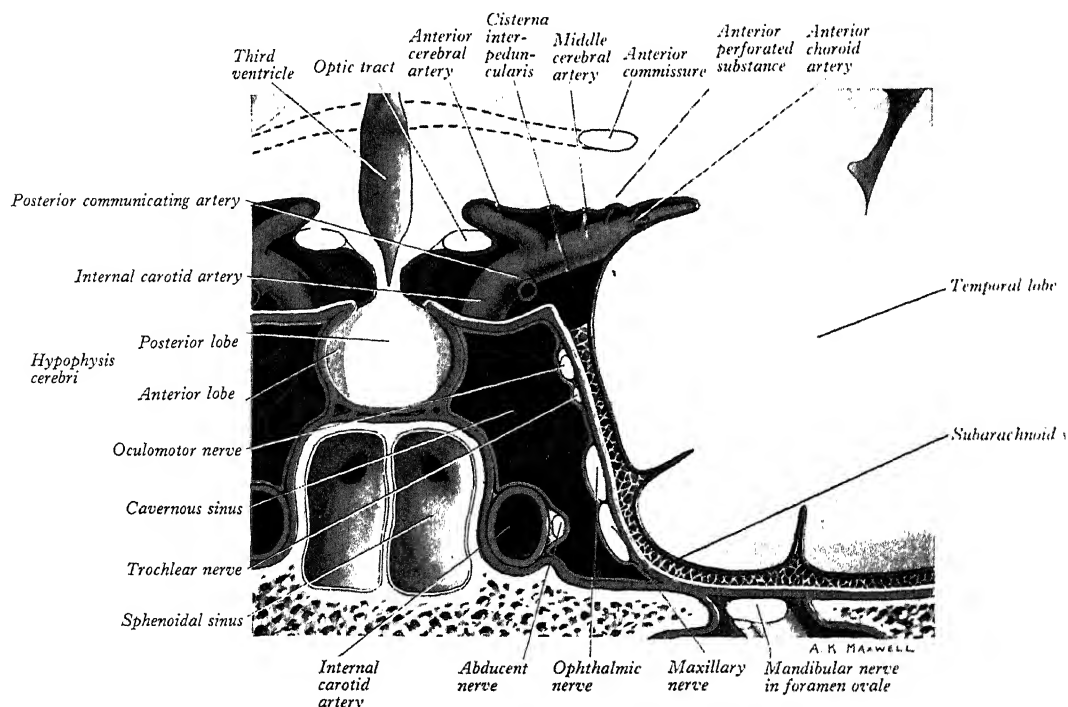
10.164 Coronal, slightly oblique section through the middle cranial fossa, showing the cavernous and cerebral portions of the internal carotid artery and the cavernous sinus: mauve = pia mater; white = arachnoid mater; green = layers of dura mater (the mesothelium of the dura mater is not indicated); blue = endothelium of cavernous sinus.

Hypophysis, Diaphragma sellae

Int. intercavernous sinus

Optic n., Ophthalmic a.

Lesser wing, orbital vein

Oculomotor n.

Trochlear n.

Trigeminal n. (Sensory ʃ

Maxillary n.

Ophthalmic n.

Trigeminal n. (Motor pa

Trigeminal ganglion

Middle meningeal a.

Sup. tympanic a.
Lesser petrosal n.

Greater petrosal n.

Abducent n., Int. caroti
Cavernous sinus

Petrosphenoidal lig.,
Sup. petrosal sinus

Fac. n. (+N. intermed.
Vestibulococh. n. and
Labyrinthine a.

Glossopharyngeal n.

Vagus n.

Accessory n., Inf. petrosal sinus

Int. carotid a.

Infundibulum, Post.
intercavernous sinus

Post. petroclinoid fold

Sup. petrosal sinus,
Trigeminal fossa

Basilar plexus, Abducent n.

Basilar sinus

Hypoglossal n.

Vertebral a.

10.165 The middle cranial fossa, viewed from above to show the termination of the internal carotid artery, its branches and the cavernous sinus. Note the plexiform nature of the 'sinus', which communicates with similar venous plexuses in the hypophyseal fossa and over the clivus. These have been exposed by partial removal of the dura mater. (See also **10.166**.)

lid from two tributaries connecting anteriorly with the facial and supraorbital veins (p. 1577). It runs with the ophthalmic artery, receiving corresponding tributaries, and traverses the superior orbital fissure to end in the cavernous sinus. The *inferior ophthalmic vein* begins in a network near the anterior region of the orbital floor and medial wall, receiving veins from the rectus inferior, obliquus inferior, lacrimal sac and eyelids; it runs back above the rectus inferior and often joins the superior ophthalmic vein but may reach the cavernous sinus. It connects with the pterygoid venous plexus by small rami through the inferior orbital fissure.
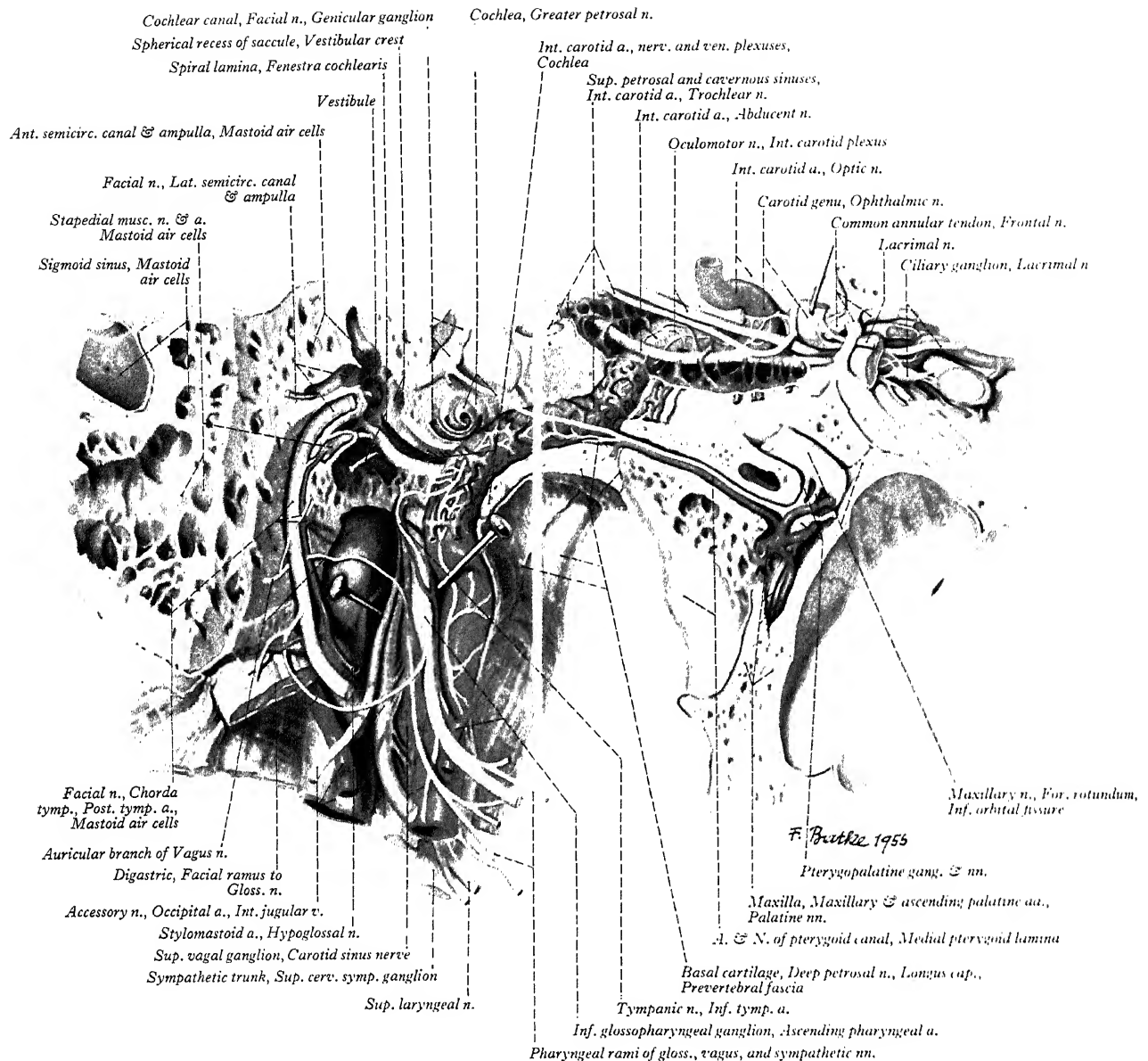
Central retinal vein. This vein first traverses the optic nerve then it leaves it to pursue a long course in the subarachnoid space before entering the cavernous sinus or the superior ophthalmic vein. It receives a *central vein* which drains the nerve while still within it.

Sphenoparietal sinuses (10.163). They are located below the periosteum of the lesser wings of the sphenoid bone, near their posterior edges. Each receives small veins from the adjacent dura mater and sometimes the frontal ramus of the middle meningeal vein; curving medially it opens into the anterior part of the cavernous sinus. It often receives connecting rami, in its middle course, from the superficial middle cerebral vein, sometimes veins from the temporal lobe and the anterior temporal diploic vein. When these connections are well developed it is a large channel.

Intercavernous sinuses. These two sinuses, anterior and posterior, interconnect the cavernous sinuses in the anterior and posterior attached borders of the diaphragma sellae; they thus complete a venous circular sinus (10.163). Small, irregular sinuses inferior to the hypophysis cerebri drain into them. Such *inferior intercavernous sinuses* were studied by Kaplan et al (1976), who emphasized their size and plexiform nature, features important in a surgical transnasal approach to the hypophysis.

Superior petrosal sinuses (10.163). These small and narrow sinuses drain the cavernous to the transverse sinuses. Leaving the posterosuperior part of the cavernous sinus, each runs posterolaterally in the attached margin of the tentorium cerebelli, crossing above the trigeminal nerve to a groove on the superior border of the petrous temporal bone; each ends by joining a transverse sinus where this curves down to become the sigmoid. It receives *cerebellar, inferior cerebral* and *tympanic veins*. It connects with the inferior petrosal sinus and basilar plexus.

Inferior petrosal sinuses. They drain the cavernous sinuses to the internal jugular veins. Each (10.163) begins postero-inferiorly at its cavernous sinus and runs back in a groove between the petrous temporal and basilar occipital bones. Traversing the anterior part of the jugular foramen it ends in the superior jugular bulb. It receives labyrinthine veins via the cochlear canaliculus and the vestibular

Cochlear canal, Facial n., Genicular ganglion

Cochlea, Greater petrosal n.

Spherical recess of saccule, Vestibular crest

Spiral lamina, Fenestra cochlearis

Int. carotid a., nerv. and ven. plexuses,
Cochlea

Sup. petrosal and cavernous sinuses,
Int. carotid a., Trochlear n.

Vestibule

Int. carotid a., Abducent n.

Ant. semicirc. canal & ampulla, Mastoid air cells

Oculomotor n., Int. carotid plexus

Int. carotid a., Optic n.

Facial n., Lat. semicirc. canal
& ampulla

Carotid genu, Ophthalmic n.

Common annular tendon, Frontal n.

Stapedial musc. n. & a.
Mastoid air cells

Lacrimal n.

Ciliary ganglion, Lacrimal n

Sigmoid sinus, Mastoid
air cells

Facial n., Chorda
tymp., Post. tymp. a.,
Mastoid air cells

Maxillary n., For. rotundum,
Inf. orbital fissure

F. Butler 1955

Auricular branch of Vagus n.

Digastric, Facial ramus to
Gloss. n.

Pterygopalatine gang. & nn.

Accessory n., Occipital a., Int. jugular v.

Maxilla, Maxillary & ascending palatine aa.,
Palatine nn.

Stylomastoid a., Hypoglossal n.

A. & N. of pterygoid canal, Medial pterygoid lamina

Sup. vagal ganglion, Carotid sinus nerve

Sympathetic trunk, Sup. cerv. symp. ganglion

Basal cartilage, Deep petrosal n., Longus cap.,
Prevertebral fascia

Sup. laryngeal n.

Tympanic n., Inf. tymp. a.

Inf. glossopharyngeal ganglion, Ascending pharyngeal a.

Pharyngeal rami of gloss., vagus, and sympathetic nn.

10.166 An oblique vertical section through the cranial base to display in lateral view the right internal carotid artery and the continuity of the venous plexus around the intraosseous and cavernous parts of the artery. (10.165 and 166 are from Pernkopf 1963, by permission of W B Saunders and Urban & Schwarzenberg.)

aqueduct and tributaries from the medulla oblongata, pons and inferior cerebellar surface. According to Browder and Kaplan (1976) the sinus is more often a plexus and sometimes drains by a vein in the hypoglossal canal to the suboccipital vertebral plexus.

Relations of structures in the jugular foramen. These are as follows: the inferior petrosal sinus is anteromedial with a meningeal branch of the ascending pharyngeal artery, and the sinus descends obliquely backwards; the sigmoid sinus is situated at the lateral and posterior part of the foramen with a meningeal branch of the occipital artery; between the sinuses are in succession, posterolaterally: the glossopharyngeal, vagus and accessory nerves (p. 1254).

Basilar venous plexus (10.163). It consists of interconnecting channels between layers of dura mater on the clivus; it interconnects the inferior petrosal sinuses and joins with the internal vertebral venous plexus. It also usually connects with the cavernous and superior petrosal sinuses at its anterior end. When marginal sinuses (p. 1589) are large they communicate anteriorly with the plexus; an almost complete circular venous channel may then surround the foramen magnum, connecting the basilar plexus intracranially to the

inferior petrosal, sigmoid and occipital sinuses and to variable extracranial vertebral plexuses in the suboccipital region.

Middle meningeal veins (or sinuses) (10.163). They communicate above with the superior sagittal sinus through its venous lacunae; below they converge and unite as frontal and parietal trunks, which accompany branches of the middle meningeal arteries in grooves on the internal parietal surfaces; but the veins are closer to bone and sometimes occupy separate grooves. The veins' situation has been said to make them liable to tears in fractures (Jones 1911). Their termination is variable. The parietal trunk may traverse the foramen spinosum to the pterygoid venous plexus; the frontal may also reach the plexus via the foramen ovale or may end in the sphenoparietal or cavernous sinus. Besides meningeal tributaries they receive small inferior cerebral veins and connect with the diploic and superficial middle cerebral veins. Browder and Kaplan (1976) state that middle meningeal 'veins' are histologically sinuses, in places almost surrounding the middle meningeal arteries; they also report frequent arachnoid granulations in them.

Surface anatomy. The superior sagittal sinus runs from the glabella

(p. 554) to the inion (6.168A). Narrow anteriorly, it widens to about 1 cm. The transverse sinus begins at the inion and runs laterally, with slight upward convexity, to the base of the mastoid process, from which the sigmoid sinus passes down just anterior to the posterior mastoid border to a point about 1 cm above its tip.

EMISSARY VEINS

Emissary veins traverse cranial apertures and make connections between venous sinuses and extracranial veins. Some are constant, others sometimes absent:

- A *mastoid emissary vein* in the mastoid foramen unites the sigmoid sinus with the posterior auricular or occipital vein.
- A *Parietal emissary vein* traverses the parietal foramen to connect the superior sagittal sinus with the veins of the scalp.
- The *venous plexus of the hypoglossal canal*, occasionally a single vein, connects the sigmoid sinus to the internal jugular vein.
- A *posterior condylar emissary vein* connects the sigmoid sinus with veins in the suboccipital triangle via the condylar canal.
- A plexus of emissary veins (*venous plexus of foramen ovale*) links the cavernous sinus to the pterygoid plexus via the foramen ovale.
- Two or three small veins traverse the foramen lacerum connecting the cavernous sinus with the pharyngeal veins and pterygoid plexus.
- A vein in the emissary sphenoidal foramen (of Vesalius) connects the same vessels.
- The *internal carotid venous plexus*, passing through the carotid canal, connects the cavernous sinus to the internal jugular vein.
- The petrosquamous sinus (p. 1584) connects the transverse sinus with the external jugular vein.
- A vein may traverse the foramen caecum (patent in about 1% of adult skulls) connecting nasal veins with the superior sagittal sinus.
- An *occipital emissary vein* usually connects the confluence of sinuses with the occipital vein through the occipital protuberance, receiving also the occipital diploic vein.
- The occipital sinus connects with variably developed veins around
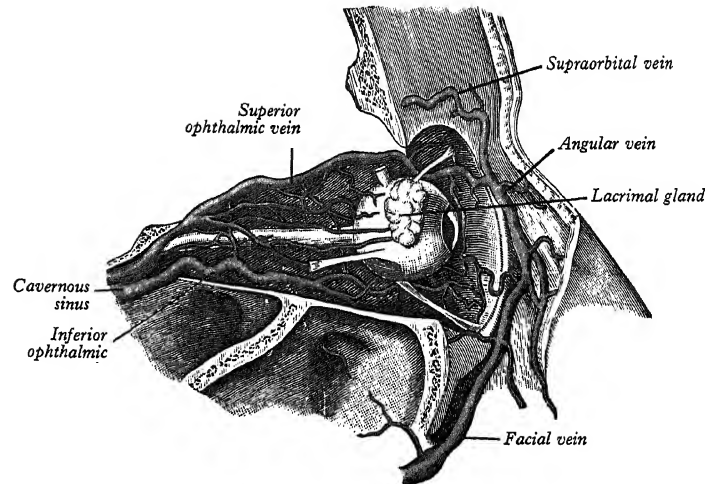
10.167 The veins of the right orbit: lateral aspect.

the foramen magnum (so-called *marginal sinuses*) and thus with the vertebral venous plexuses, an alternative venous drainage when the jugular vein is blocked or tied.
- The ophthalmic veins are potentially emissary, since they connect intracranial to extracranial veins; but parietal emissary veins, included here, are usually minute and do not appear to connect with veins of the scalp in corrosion casts.

These connections are significant in the spread of infection from extracranial foci to venous sinuses. The success of a ligature of the internal jugular vein, to limit the spread of some oral and pharyngeal pathologies, depends on the adequacy of the collateral drainage.

OF THE UPPER LIMBS

Veins are conveniently grouped as *superficial* and *deep* but these are widely interconnected. The superficial veins are subcutaneous in the superficial fascia; deep veins accompany arteries between the muscles of the limb. Both groups have valves, which are more numerous in veins.

SUPERFICIAL VEINS OF THE UPPER LIMB

Superficial veins (10.168, 169) include the cephalic, basilic, median cubital and additional antebrachial veins and their tributaries.

Dorsal digital veins pass along the sides of the fingers, joined by oblique branches; they unite from the adjacent sides of digits into three dorsal metacarpal veins (10.168), which form a *dorsal venous network* over the metacarpus; this is joined laterally by a dorsal digital vein from the radial side of the index finger and both dorsal digital veins of the thumb and is prolonged proximally as the cephalic vein. Medially a dorsal digital vein from the ulnar side of minimus joins the network, which drains proximally into the basilic vein. A vein often connects the central parts of the network to the cephalic near midforearm.

Palmar digital veins connect to the dorsal by oblique intercapitular veins passing between metacarpal heads; they also drain to a plexus superficial to the palmar aponeurosis, extending over both thenar and hypothenar regions.
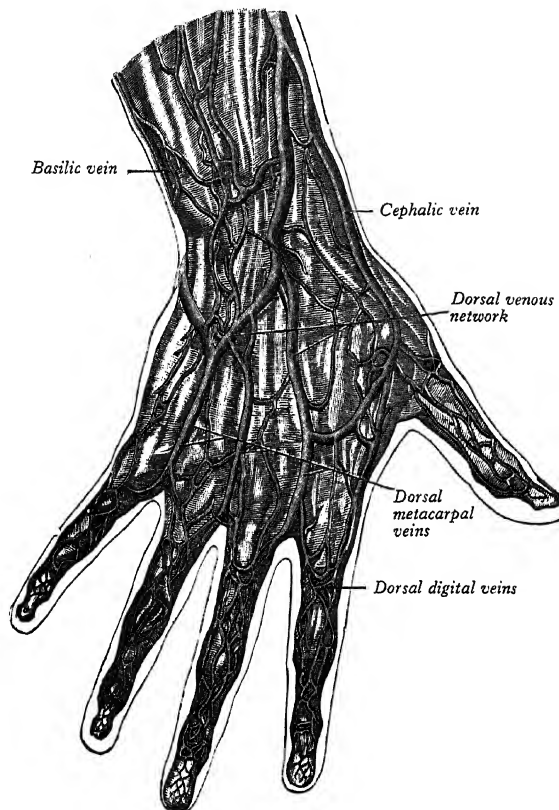
Cephalic vein (10.168, 169). Commonly formed over the 'anatomical snuff box', it curves proximally from the radial end of the dorsal plexus round the forearm's radial side to its ventral aspect, receiving veins from both aspects. Distal to the elbow a branch, the *median cubital vein*, joined by a branch from the deep veins, diverges

proximomedially to reach the basilic vein. The cephalic ascends in front of the elbow superficial to a groove between the brachioradialis and biceps, crosses superficial to the lateral cutaneous nerve of the forearm, ascends lateral to the biceps and between pectoralis major and the deltoid, where it adjoins the deltoid branch of the thoracoacromial artery. Entering the infraclavicular fossa to pass behind the clavicular head of pectoralis major, it pierces the clavipectoral fascia, crosses the axillary artery and joins the axillary vein just below clavicular level. It may connect with the external jugular by a branch anterior to the clavicle. Sometimes the median cubital vein is large, transferring most blood from the cephalic to the basilic vein, the proximal cephalic vein then being absent or much diminished.

Accessory cephalic vein. Arising in a dorsal forearm plexus or from the ulnar side of the dorsal venous network in the hand, this joins the cephalic distal to the elbow. It may spring from the cephalic proximal to the carpus and rejoin it later. A large oblique vein often connects the basilic and cephalic veins dorsally in the forearm.

Basilic vein (10.169). Beginning medially in the hand's dorsal venous network, it ascends posteromedially in the forearm inclining forwards to the anterior surface distal to the elbow. Joined by the median cubital vein, it ascends superficially to and between biceps and pronator teres; filaments of the medial cutaneous nerve of the forearm pass here, in front and behind it. It ascends medial to biceps and perforates the deep fascia about midway in the arm, continuing medial to the brachial artery to the lower border of teres major, there becoming the axillary vein. (Its relation to the brachial veins is variable; see p. 1590.)

Median vein of the forearm (10.169). It drains the superficial palmar venous plexus. It ascends anterior in the forearm to join the

10.168 The veins of the dorsum of the hand.

The radial veins are smaller, receiving the deep dorsal veins of the hand; ulnar veins drain the deep palmar venous arch, connecting with superficial veins near the wrist; near the elbow they receive the anterior and posterior interosseous artery companion veins; a large branch connects them to the *median cubital vein*.

Brachial veins. They flank the brachial artery, with tributaries similar to the arterial branches; near the lower margin of subscapularis they join the axillary vein, the medial one, however, often joining the basilic before it becomes the axillary.

These deep veins have numerous anastomoses with each other and with the superficial veins.

Axillary vein. This large vein is the continuation of the basilic; it begins at the lower border of teres major, and ascends to the outer border of the first rib, where it becomes the subclavian. Near subscapularis the brachial vein joins it and, near its costal end, the cephalic; other tributaries follow the axillary arterial branches. It is

basilic or median cubital vein; it may divide distal to the elbow to join both.

Surface anatomy

Superficial veins are usually visible until they pierce the deep fascia. Larger ones are obvious when the limb is dependent and its muscles contracted, driving blood from the deep to the superficial veins.

Clinical anatomy

Blood sampling, blood transfusion and intravenous injection are commonly done near the elbow or more distally in the forearm; the largest vein is usually the median cubital. The cubital veins are also used for cardiac catheterization for many purposes. Equally useful for such procedures is the cephalic vein where it is superficial to the distal end of the radius in the 'anatomical snuffbox'. The cephalic vein, a little proximal to the snuff box, is the site with many advantages for an indwelling cannula or fine tube when a lengthy period is contemplated; the position of the arm, forearm and hand is optimal for this purpose.

DEEP VEINS OF THE UPPER LIMB

Deep veins (venae comitantes) accompany arteries, usually in pairs, flanking the artery and connected by short transverse links. Since much blood from the upper limb is returned by the superficial veins, the deep ones are relatively small.

Deep veins of the hand. Superficial and deep palmar arterial arches are accompanied by superficial and deep palmar venous arches, receiving the corresponding branches. Thus common palmar digital veins join the superficial arch and palmar metacarpal veins join the deep arch. Deep veins accompanying the dorsal metacarpal arteries first receive perforating branches from the palmar metacarpal veins and then end in the radial veins and the dorsal venous network.
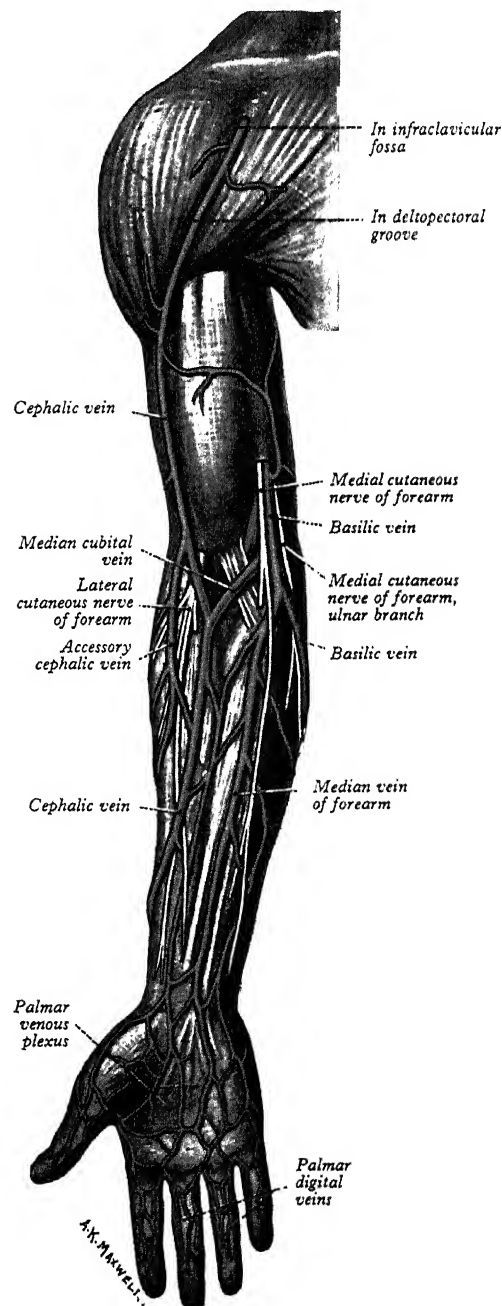
Deep veins of the forearm. Running with the radial and ulnar arteries they drain respectively the deep and superficial palmar venous arches; they unite near the elbow as paired *brachial veins.*

10.169 The superficial veins of the right upper extremity: anterior aspect.

medial to the axillary artery, which it partly overlaps; between them are the medial pectoral nerve, medial cord of the brachial plexus, the ulnar nerve and the medial cutaneous nerve of the forearm. The medial cutaneous nerve of the arm is medial to the vein; the lateral group of axillary lymph nodes is posteromedial. It has a pair of valves near its distal end; valves also occur near the ends of the cephalic and subscapular veins.

Subclavian vein (10.92). Continuing the axillary, this vein extends from the outer border of the first rib to the medial border of scalenus anterior, where it joins the internal jugular to form the brachiocephalic vein. **Anterior** are the clavicle and subclavius, **posterosuperior** the subclavian artery, separated by the scalenus

anterior and phrenic nerve; **inferior** are the first rib and pleura. The vein usually has a pair of valves about 2 cm from its end. Its tributaries are the external jugular, dorsal scapular and sometimes the anterior jugular; occasionally a small branch ascends in front of the clavicle from the cephalic vein. At its junction with the internal jugular the left subclavian receives the thoracic duct, the right subclavian vein and the right lymphatic duct.

Surface anatomy

The vein can be projected as a broad band, convex upwards, from just medial to the midclavicular point to the medial edge of the clavicular attachment of sternocleidomastoid.
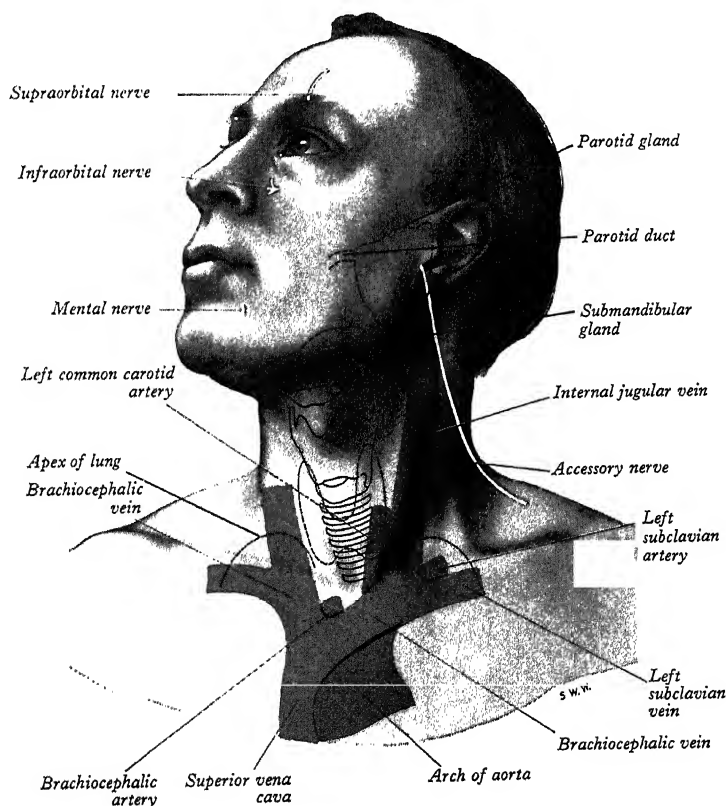
Brachiocephalic veins

The brachiocephalic (innominate) veins, two large vessels at the junction of the neck and thorax, are the united trunks of the internal jugular and subclavian veins. Both are devoid of valves.

Right brachiocephalic vein (10.170). About 2.5 cm long, it begins posterior to the sternal end of the right clavicle, and descends almost vertically to join the left brachiocephalic forming the superior vena cava posterior to the lower border of the first right costal cartilage, near the right sternal border. It is anterolateral to the brachiocephalic artery and right vagus nerve. The right pleura, phrenic nerve and internal thoracic artery are posterior to it above, becoming lateral below. Its tributaries are the right vertebral, internal thoracic, inferior thyroid and sometimes the first right posterior intercostal veins.

Left brachiocephalic vein (10.170). Some 6 cm long, it begins posterior to the sternal end of the left clavicle, anterior to the cervical
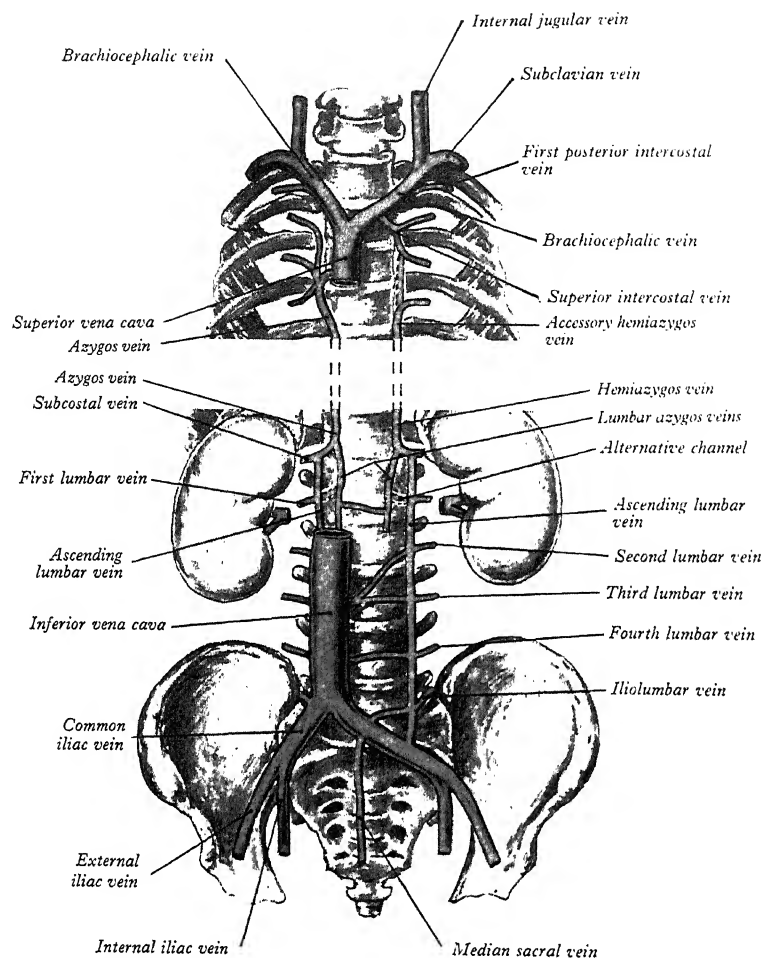
pleura. It descends obliquely to the right, posterior to the upper half of the manubrium sterni, to the sternal end of the first right costal cartilage, uniting here with the right brachiocephalic to form the superior vena cava. It is separated from the left sternoclavicular joint and manubrium by the sternohyoid and sternothyroid, the thymus or its remains and areolar tissue; terminally it is overlapped by the right pleura. It crosses anterior to the left internal thoracic, subclavian and common arteries, left phrenic and vagus nerves, trachea and brachiocephalic artery. The aortic arch is inferior to it. The vein's tributaries are the left vertebral, internal thoracic, inferior thyroid, superior intercostal, sometimes the first left posterior intercostal, thymic and pericardial veins.

Surface anatomy. The brachiocephalic veins can be projected as broad bands 1.5 cm wide from the sternal ends of the clavicles to the parasternal lower border of the first right costal cartilage.

Supraorbital nerve

Infraorbital nerve

Mental nerve

Left common carotid artery

Apex of lung

Brachiocephalic vein

Parotid gland

Parotid duct

Submandibular gland

Internal jugular vein

Accessory nerve

Left subclavian artery

Left subclavian vein

Brachiocephalic vein

Brachiocephalic artery

Superior vena cava

Arch of aorta

10.170 The surface projections of some of the important structures in the face, neck and upper part of the thorax. The apices of the lungs, the thyroid, submandibular and parotid glands and the parotid duct are indicated in interrupted dotted outline; the hyoid bone, the thyroid and cricoid cartilages and the rings of the trachea are shown in continuous outline.

Internal jugular vein

Brachiocephalic vein

Subclavian vein

First posterior intercostal vein

Brachiocephalic vein

Superior intercostal vein

Accessory hemiazygos vein

Superior vena cava

Azygos vein

Hemiazygos vein

Azygos vein

Subcostal vein

Lumbar azygos veins

Alternative channel

First lumbar vein

Ascending lumbar vein

Ascending lumbar vein

Second lumbar vein

Third lumbar vein

Inferior vena cava

Fourth lumbar vein

Iliolumbar vein

Common iliac vein

External iliac vein

Internal iliac vein

Median sacral vein

10.171 Schema showing the superior and inferior extremities of the azygos system of veins and their principal associated veins. The intervening parts have been omitted because schemata of this region are often topographically misleading. Much variation occurs in the transthoracic parts of the azygos and hemiazygos veins, in terms of numbers of radicles, levels of transmedian crossing, etc. Schemata are usually misleading. That depicted by painting in 10.172 is the most common condition.

Variations. The brachiocephalic veins may enter the right atrium separately, the right vein descending like a normal superior vena cava; a left superior vena cava may have a slender connection with the right and then cross the left side of the aortic arch to pass anterior to the left pulmonary hilum before turning to enter the right atrium. It replaces the oblique atrial vein and coronary sinus and receives all the latter's tributaries. This abnormality, due to persistence of an early fetal condition, is normal in birds and some mammals. The left brachiocephalic vein sometimes projects above the manubrium (more frequently in childhood), crossing the suprasternal fossa in front of the trachea.

Internal thoracic (mammary) veins

The internal thoracic veins are venae comitantes to the inferior half of the internal thoracic artery; they have several valves. Near the third costal cartilages the veins unite to ascend medial to the artery, ending in their brachiocephalic vein (**10.71, 95**). Tributaries correspond to branches of the artery (p. 1534), and include a pericardiophrenic vein.

Inferior thyroid veins

The inferior thyroid veins arise in a glandular venous plexus,

which also connects with the middle and superior thyroid veins (**10.71**). These veins form a *pretracheal plexus* from which the left inferior vein descends to join the left brachiocephalic, the right descending obliquely across the brachiocephalic artery to the right brachiocephalic vein, at its junction with the superior vena cava; the inferior thyroid veins often open in common into the vena cava or left brachiocephalic vein. They drain the oesophageal, tracheal and inferior laryngeal veins and have valves at their terminations.

Left superior intercostal vein

The left superior intercostal vein drains the second and third (sometimes fourth) left posterior intercostal veins, ascending obliquely forwards across the left aspect of the aortic arch, lateral to the left vagus, medial to the left phrenic nerve, to open into the left brachiocephalic vein (**10.71**). It usually receives the left bronchial veins, sometimes the left pericardiacophrenic; it connects inferiorly with the accessory hemiazygos vein.

Superior vena cava

The superior vena cava is about 7 cm in length, formed by the junction of the brachiocephalic veins, and has no valves. It returns

to the heart blood from the superior half of the body. It begins behind the lower border of the first right costal cartilage near the sternum, descends vertically behind the first and second intercostal spaces, ending in the upper right atrium behind the third right costal cartilage; its inferior half is within the fibrous pericardium, which it pierces level with the second costal cartilage. Covered anterolaterally by serous pericardium from which projects a *retrocaval recess*, it is slightly convex to the right (10.66, 68–71).

Relations. Anterior are the anterior margins of the right lung and pleura, the pericardium intervening below; these separate the vein from the internal thoracic artery and first and second intercostal spaces, and second and third costal cartilages; posteromedial are the trachea and right vagus nerves and posterolateral the right lung and pleura; posterior is the right pulmonary hilum. Right lateral are the right phrenic nerve and pleura, left lateral the brachiocephalic artery and ascending aorta, the latter overlapping it.

Surface anatomy. The superior vena cava, 2 cm wide, is partly behind but projects well beyond the right sternal margin, from the lower border of the first to the lower border of the third right costal cartilage. Its lateral border is visible in anteroposterior radiographs.

Tributaries. These are: the azygos vein and small veins from the pericardium and other mediastinal structures.

Azygos vein (10.171–173).

An origin from the posterior aspect of the inferior vena cava, at or below the level of the renal veins, is to be expected from its development but it is not constant (Gladstone 1929). Such a lumbar azygos vein frequently occurs, ascending anterior to the upper lumbar vertebrae. The vein may pass behind the right crus of the diaphragm or pierce it. It may traverse the aortic opening on the right of the cisterna chyli. Anterior to the twelfth thoracic vertebral body it is joined by a large vessel formed by the right ascending lumbar and right subcostal veins, which passes forward and right of the twelfth thoracic vertebra behind the right crus. This common trunk may, in the absence of a lumbar azygos, form the azygos itself. Whatever its origin, the azygos vein ascends in the posterior mediastinum to the fourth thoracic vertebra, arching forward above the right pulmonary hilum to end in the superior vena cava, before the latter pierces the pericardium. It is **anterior** to the lower eight thoracic vertebral bodies (see below), anterior longitudinal ligament and right posterior intercostal arteries. **Right lateral** are the right greater splanchnic nerve, lung and pleura; **left lateral** in most of its course are the thoracic duct and aorta and, where it arches forward, the oesophagus, trachea and right vagus. In the lower thorax it is covered anteriorly by a recess of the right pleural sac and oesophagus, emerging from behind the latter to ascend behind the right hilum (10.173). Because of the closeness of the azygos vein to the right posterolateral aspect of the descending thoracic aorta, aortic pulsations may assist venous return in azygos and hemiazygos veins.

Tributaries. The azygos vein drains: the right posterior intercostal veins except the first, the veins from the second to fourth intercostal spaces usually via a right superior intercostal vein, the hemiazygos and accessory hemiazygos veins, oesophageal, mediastinal and pericardial veins and, near its end, right bronchial veins. When it begins as a lumbar azygos, the common trunk formed by the right ascending lumbar and subcostal veins is its largest tributary. Imperfect valves occur in the azygos vein, some tributaries having complete valves.

Hemiazygos vein. It starts on the left like the azygos; ascending anterior to the vertebral column to the eighth thoracic level, it crosses the column posterior to the aorta, oesophagus and thoracic duct to end in the azygos vein. Its tributaries are the lower three posterior intercostal veins, a common trunk formed by the left ascending lumbar and subcostal veins and oesophageal and mediastinal rami. Its lower end often connects with the left renal vein.

Accessory hemiazygos vein. It descends to the left of the vertebral column, receiving veins from the fourth (or fifth) to eighth intercostal spaces and sometimes the left bronchial veins. It crosses the seventh thoracic vertebra to join the azygos vein. It sometimes joins the hemiazygos, their common trunk opening into the azygos vein.

Variations of the azygos veins. They vary much in their mode of origin, course, tributaries, anastomoses and termination. For a survey consult Grzybiak et al (1975), who consider the accessory
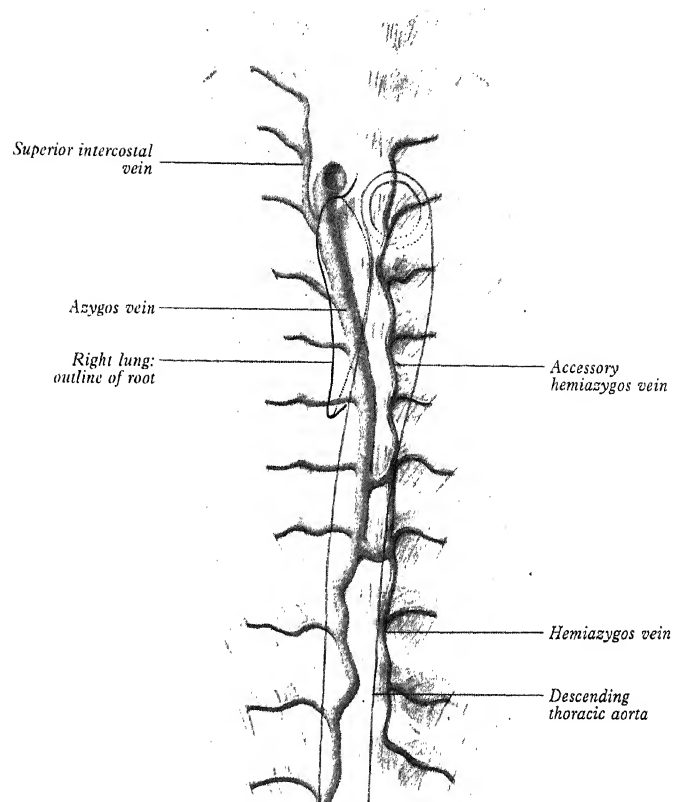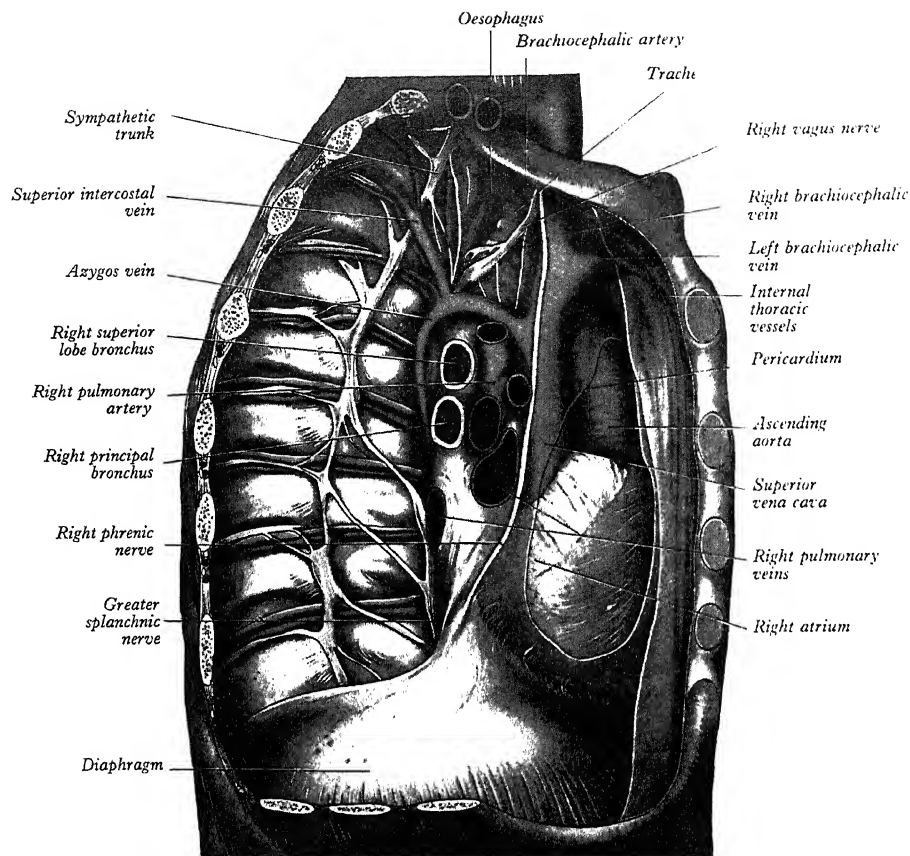

10.172 A frequent (perhaps the commonest) course followed by the intra-thoracic azygos, hemiazygos and accessory hemiazygos veins. Outlines of the root of the right lung and descending thoracic aorta are included. (Dissection by M C E Hutchinson, Guy's Hospital Medical School, London.)

hemiazygos most variable, draining into the left brachiocephalic, azygos or hemiazygos. The arrangement shown in 10.172 represents a common pattern. In about 1 or 2% of subjects according to Anson (1963) there are left and right independent azygos veins (the early embryonic form) and occasionally a single azygos without hemiazygos tributaries, in a midline position. In more than 95% a main 'right-sided' azygos and at least some representative of hemiazygos veins exist. The latter vary, one or the other being absent or poorly developed. Retro-aortic transvertebral connections from hemiazygos and accessory hemiazygos veins to the azygos are also extremely variable; there may be from one to five, or more; when either hemiazygos is absent, intercostal veins involved cross vertebral bodies to end in the azygos. These transvertebral routes are often very short, since the azygos vein is more commonly anterior to the vertebral column (Anson 1963) and often passes left of the midline in part of its course.

Posterior intercostal veins

The posterior intercostal veins accompany their arteries in eleven pairs. Approaching the vertebral column each vein receives a posterior tributary returning blood from the dorsal muscles and skin and vertebral venous plexuses (10.111, 173). On both sides the first posterior intercostal vein ascends anterior to the first rib's neck, arching forward above the pleural dome to end in the ipsilateral brachiocephalic or vertebral vein. On the right the second, third and often fourth, form a right superior intercostal vein joining the arch of the azygos vein. Veins from the lower spaces drain directly to it. On the left the second and third (sometimes fourth) form a left superior intercostal vein (p. 1592). Veins from the fourth (or fifth) to eighth spaces end in the accessory hemiazygos vein, veins from the lower three spaces in the hemiazygos.

Oesophagus
Brachiocephalic artery
Trachea
Sympathetic trunk
Superior intercostal vein
Azygos vein
Right superior lobe bronchus
Right pulmonary artery
Right principal bronchus
Right phrenic nerve
Greater splanchnic nerve
Diaphragm

Right vagus nerve
Right brachiocephalic vein
Left brachiocephalic vein
Internal thoracic vessels
Pericardium
Ascending aorta
Superior vena cava
Right pulmonary veins
Right atrium

10.173 The right aspect of the mediastinum. The right lung and most of the right pleura have been removed and a large opening made into the pericardial sac to expose the heart. In this specimen the fourth right posterior intercostal vein did not join the superior intercostal vein.

Posterior intercostal veins are so called to distinguish them from small *anterior intercostal veins* which are tributaries of the internal thoracic and musculophrenic veins.

Clinical anatomy. In obstruction of the upper inferior vena cava, the azygos and hemiazygos veins and vertebral venous plexuses are the main collateral channels maintaining venous circulation, by connecting superior and inferior venae cavae and communicating with the common iliac by ascending lumbar veins and with many tributaries of the inferior vena cava.

Bronchial veins

Usually two on each side, the bronchial veins drain blood from larger bronchi and from hilar structures. The right bronchial veins join the end of the azygos, the left join the left superior intercostal or hemiazygos vein. Some blood carried to the lungs by bronchial arteries returns via the pulmonary veins (see p. 1674).

Posterior external plexuses
Spine
Anterior internal plexus
Posterior internal plexus
Intervertebral vein
Segmental vein
Basivertebral vein
Anterior external plexus
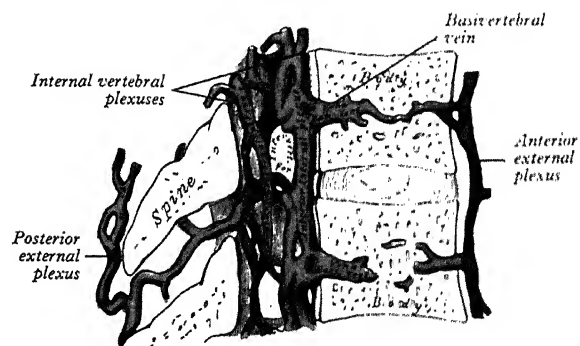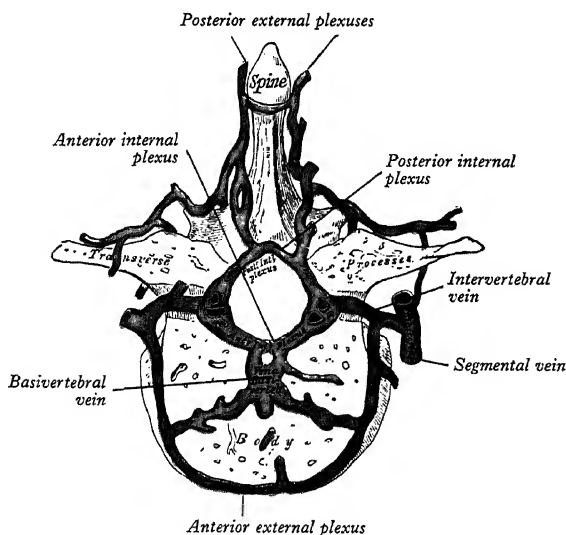
10.174 Transverse section through the body of a thoracic vertebra showing the vertebral venous plexuses and basivertebral veins.

Basivertebral vein
Internal vertebral plexuses
Anterior external plexus
Spine
Posterior external plexus

10.175 Median sagittal section through two thoracic vertebrae showing the vertebral venous plexuses and basivertebral veins.

VEINS OF THE VERTEBRAL COLUMN

Veins of the vertebral column form intricate plexuses along the entire column, external and internal to the vertebral canal. Both groups are devoid of valves, anastomose freely with each other and join the intervertebral veins (10.174, 175). Interconnections are widely established between these plexuses and longitudinal veins early in fetal life.

External vertebral venous plexuses

The external vertebral venous plexuses are anterior and posterior, anastomosing freely, and are most developed in the cervical region. *Anterior external plexuses* are anterior to the vertebral bodies, communicating with basivertebral and intervertebral veins and receiving tributaries from vertebral bodies. *Posterior external plexuses* lie posterior to vertebral laminae and around spines, transverse and articular processes. They anastomose with the internal plexuses and join the vertebral, posterior intercostal and lumbar veins.

Internal vertebral venous plexuses

The internal vertebral venous plexuses occur between the dura mater and vertebrae, receiving tributaries from the bones, red bone marrow and spinal cord. They form a denser network than the external plexuses and are arranged vertically as four interconnecting longitudinal vessels, two in front, two behind.

The *anterior internal plexuses* are large plexiform veins on the posterior surfaces of vertebral bodies and intervertebral discs, flanking the posterior longitudinal ligament; under this they are connected by transverse branches, into which the large basivertebral veins open. The *posterior internal plexuses*, on each side in front of the vertebral arches and ligamenta flava, anastomose with the posterior external plexuses by veins passing through and between the ligaments. The internal plexuses interconnect by venous rings near each vertebra. Around the foramen magnum they form a dense network connecting with: vertebral veins, occipital and sigmoid sinuses, basilar plexus, venous plexus of the hypoglossal canal and the condylar emissary veins.

Basivertebral veins

The basivertebral veins emerge from the posterior foramina of vertebral bodies. They are large and tortuous channels in bone, like those in cranial diploë. The trabecular bone in vertebral bodies contains much haemopoietic tissue. The basivertebral veins also drain into the anterior external vertebral plexuses through small openings in the vertebral bodies. Posteriorly they form one or two short trunks opening into the transverse branches uniting anterior internal vertebral plexuses. They enlarge in advanced age.

Intervertebral veins

The intervertebral veins accompany the spinal nerves through intervertebral foramina, draining the spinal cord and internal and external vertebral plexuses, and ending in the vertebral, posterior intercostal, lumbar and lateral sacral veins. Whether the basivertebral or intervertebral veins contain effective valves is uncertain but experiment strongly suggests that their blood flow can be reversed (Batson 1957). This may explain how pelvic neoplasms, in particular, may metastasize in vertebral bodies, the cells spreading into the internal vertebral plexuses by connections with the pelvic veins when blood flow is temporarily reversed by raised intra-abdominal pressure or postural alterations.

Veins of the spinal cord

The veins of the spinal cord lie in the pia mater, forming a tortuous venous plexus. In this there are:

- two *median longitudinal veins*, one near the anterior median fissure, the other behind the posterior median septum
- two *anterolateral* and two *posterolateral longitudinal veins* respectively behind the ventral and dorsal spinal nerve roots.

They drain to internal vertebral plexuses, and thence to intervertebral veins. Near the skull they unite into two or three small veins joined to the vertebral veins and ending in inferior cerebellar veins or the inferior petrosal sinuses.

Veins of the lower limbs can be subdivided, like those of the upper, into *superficial* and *deep* groups, the superficial being subcutaneous in the superficial fascia, the deep veins (beneath the deep fascia) accompanying major arteries. Both have valves, more numerous in deep veins and also more numerous than in the upper limb.

SUPERFICIAL VEINS OF THE LOWER LIMBS

The principal named superficial veins are the great and small saphenous; their numerous tributaries are mostly (but not wholly) unnamed; named vessels will be noted (10.176, 177). (For variations consult Kosinski 1926.) As in the upper limb the vessels will be described centripetally from peripheral to major drainage channels.

Dorsal digital veins receive, in the clefts between the toes, rami from the plantar digital veins and then join to form dorsal metatarsal veins, which are united across the proximal parts of the metatarsal bones in a *dorsal venous arch*. Proximal to this is an irregular *dorsal venous network* receiving tributaries from deep veins and continuous proximally with a venous network in the leg. At each side of the foot this network connects with *medial* and *lateral marginal veins*, both formed mainly by veins from more superficial parts of the sole. In the sole superficial veins form a *plantar cutaneous arch* across the roots of the toes and also drain into the medial and lateral marginal veins. Proximal to the plantar arch is a *plantar cutaneous venous plexus*, especially dense in the fat of the heel; this connects with the plantar cutaneous venous arch and other deep veins, but drains mainly into the marginal veins.

Great (long) saphenous vein

The great saphenous vein starts inferiorly (below) as a continuation of the medial marginal vein and ends in the femoral vein a short distance distal to the inguinal ligament (see below), being thus the body's longest vein (10.176). It ascends about 2.5–3 cm anterior to the tibial malleolus, crosses the distal third of the medial surface of the tibia obliquely to its medial border, then ascends a little behind the border to the knee; proximally it is posteromedial to the medial tibial and femoral condyles, then ascends the medial aspect of the thigh; after traversing the saphenous opening (p. 873) it finally opens into the femoral vein. The so-called 'centre' of the opening is often said to be 2.5–3.5 cm inferolateral to the pubic tubercle; and the vein is then held to be represented by a line drawn from this to the femoral adductor tubercle. However, the saphenous opening, as noted elsewhere, varies greatly in size and disposition and its imagined centre has proved a poor indicator of the saphenofemoral junction.

In its course through the thigh the great saphenous vein has branches of the medial femoral cutaneous nerve accompanying it: at the knee the saphenous branch of the descending genicular artery and, in the leg and foot, the saphenous nerve, are anterior to it. The vein is often duplicated, especially distal to the knee. It has from 10 to 20 valves, which are more numerous in the leg than the thigh. One is present just before it pierces the cribriform fascia, another at its junction with the femoral vein. In almost its entire extent the vein lies in superficial fascia, but it has many connections with the deep veins, especially in the leg (see below).

Clinical anatomy. Royle and Eisher (1981) made a careful quantitative study in 167 flush ligations in 136 subjects noting, in particular, the relative positions of the pubic tubercle, the venous junction and the inguinal skin crease. They concluded that a correctly placed incision for flush saphenofemoral ligation should be made
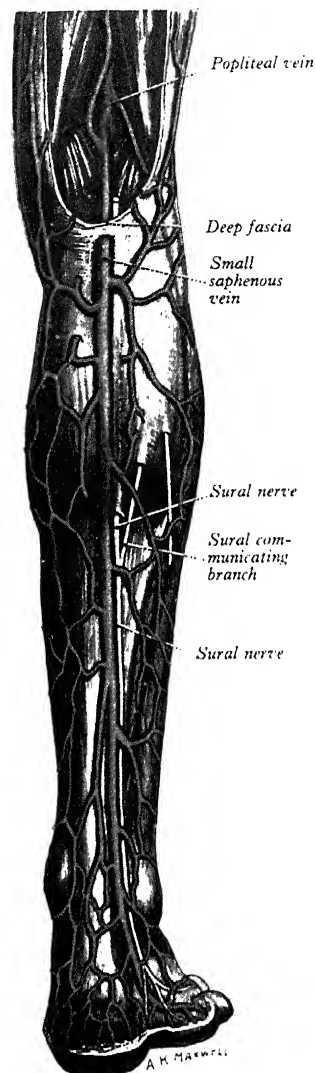
10.176 The great saphenous vein and its tributaries.
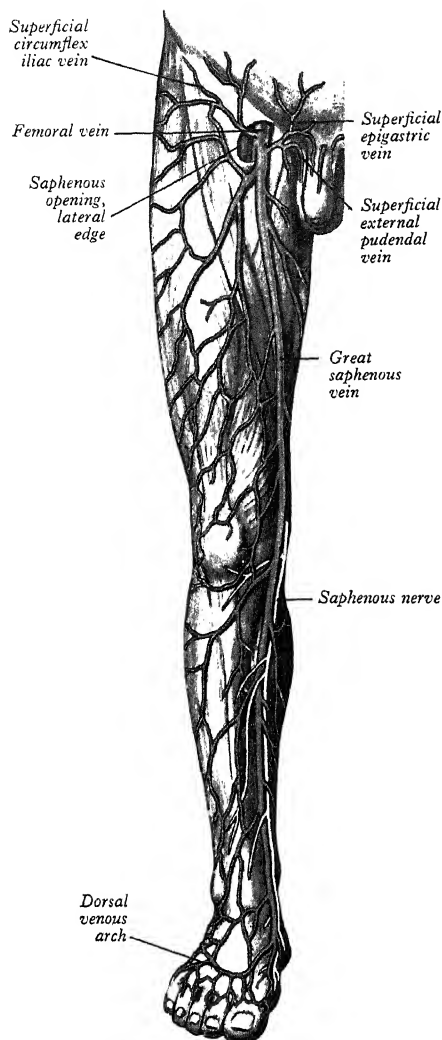
10.177 The small saphenous vein and its tributaries.

1 cm above, and parallel to, the inguinal skin crease, centring the incision at a point 4 cm lateral to and level with the pubic tubercle.

Tributaries. At the ankle the great saphenous drains the sole by medial marginal veins. In the leg it often connects with the small saphenous vein and with deep veins through *perforating veins*. Just distal to the knee it usually has three large tributaries: one from the front of the leg, a second from the tibial malleolar region (connecting with some of the 'perforating' veins) and a third from the calf (communicating with the small saphenous vein). The second of these forms below in a fine network or 'corona' of delicate veins over the medial malleolus and then ascends the medial aspect of the calf as the '*posterior arch vein*' of Dodd and Cockett (1976); the clinical importance of its connections with posterior tibial venae comitantes by a series of perforating (communicating) veins was emphasized by Platz and Adelmann (1976), who proposed the term '*vena arcuata cruris posterior*'. The clinical significance of the latter should be reaffirmed, with relevant points concerning other venous channels in the leg. Although Platz and Adelmann (1976) mentioned 3–6 perforating veins, it has been indicated that three are most usual, being equally spaced between the medial malleolus and the midcalf; more than three was termed 'most uncommon' and an arch vein perforator above midcalf 'extremely rare'. The posterior crural arch vein was first illustrated by Leonardo da Vinci and his name is often applied to the vein in some surgical circles.

Above the posterior crural arch vein, perforating veins join the great saphenous or one of its main tributaries at two main sites. The

first is at a level in the upper calf indicated by its name, the *tibial tubercle perforator* (*Boyd's perforator*); the second is in the lower/intermediate third of the thigh where it perforates the deep fascial roof of the subsartorial canal to join the femoral vein (*Hunterian perforator*).

In the thigh the great saphenous vein receives many tributaries; some open independently, whilst others converge to form large named channels that frequently pass towards the basal half of the femoral triangle before joining the great saphenous near its termination. These may be grouped thus: one or more large posteromedial tributaries, one or more large anterolateral tributaries, four or more peri-inguinal veins. The *posteromedial vein of the thigh*, large and sometimes double, drains a large superficial region indicated by its name (as have the other tributaries) radiological and surgical significance. One of its lower radicles is often continuous with the small saphenous vein. The posteromedial vein is sometimes (perhaps unhelpfully) named the *accessory saphenous vein* with greater emphasis on its variability of form and level of junction with the great saphenous. Some restrict the term accessory to a lower (more distal) posteromedial branch when two (or more) are present. Another large vessel, the *anterolateral vein of the thigh* (*anterior femoral cutaneous vein*), usually commences from an anterior network of veins in the distal thigh and crosses the apex and distal half of the femoral triangle to reach the great saphenous vein. As the latter traverses its saphenous opening (**10.176**), it is joined by the superficial epigastric, superficial circumflex iliac and superficial

external pudendal veins. Their mode of union varies. Superficial epigastric and circumflex iliac veins drain the inferior abdominal wall, the latter also receiving tributaries from the proximolateral region of the thigh; superficial external pudendal veins drain part of the scrotum, one being joined by the superficial dorsal vein of the penis. The deep external pudendal vein joins the great saphenous in its opening.

A *thoraco-epigastric vein* lies along the anterolateral aspect of the trunk and connects the superficial epigastric or femoral vein to the lateral thoracic veins, thus connecting femoral and axillary veins and hence the superior and inferior vena caval fields of drainage. It is held to be in line with the primitive mammary ('milk') ridge which extends from the axilla to the pubic region (p.296).

Small (short) saphenous vein (10.177)

The small saphenous vein begins posterior to the lateral malleolus, as a continuation of the lateral marginal vein. In the lower third of the calf it ascends lateral to the tendo calcaneus, lying on the deep fascia and covered only by superficial fascia and skin. Inclining medially to the midline of the calf it penetrates into the deep fascia within which it ascends on the gastrocnemius, only emerging between the deep fascia and gastrocnemius gradually at about the junction of the intermediate and proximal thirds of the calf (usually well below the lower limit of the popliteal fossa). Continuing its ascent it passes between the heads of the gastrocnemius, then proceeds to its termination in the popliteal vein, 3–7.5 cm above the knee joint in the popliteal fossa.

Tributaries. The small saphenous vein connects with deep veins on the dorsum of the foot, receives many cutaneous tributaries in the leg and sends several rami proximally and medially to join the great saphenous vein. Sometimes a communicating branch from it ascends medially to the accessory saphenous vein (see above); this may be the main continuation of the small saphenous. In the leg the small saphenous lies near the sural nerve. It has 7–13 valves, one near its termination. Its mode of ending is variable; it may join the great saphenous vein in the proximal thigh or it may bifurcate, one branch joining the great saphenous, the other the popliteal or deep posterior femoral veins; sometimes it ends distal to the knee in the great saphenous or deep sural muscular veins.

Clinical anatomy. In a standing position, venous return from the lower limb depends largely on muscular activity (p. 1466), especially contraction of the calf muscles, known as the 'calf pump', whose efficiency is aided by the tight sleeve of deep fascia. 'Perforating' veins have been noted that connect the great saphenous with the deep veins, particularly near the ankle, distal calf and knee regions. In these channels valves are arranged to prevent flow of blood from deep to superficial veins. At rest, pressure in a superficial vein is equal to the height of the column of blood extending therefrom to the heart. When calf muscles contract, blood is pumped proximally in the deep veins but is normally prevented from flowing into superficial veins by the valves in the perforating veins; during relaxation blood can be aspirated from superficial into deep veins. If the valves in the perforating veins become incompetent, these veins become 'high pressure leaks' during muscular contraction; this transmission of high pressure in deep veins to superficial veins results in dilatation and blood stagnation in the latter, producing varicosities, anoxia of tissues and ultimately varicose ulceration. In operative treatment of severe varicose veins and ulcers, perforating veins must be ligatured. Similar perforating connections occur in the anterolateral region and varicosities may also occur here (Cockett 1956; Green et al 1958). Veins connecting the great saphenous to the femoral vein, in the adductor canal, may also become varicose (Dodd & Cockett 1956; Dodd 1959).

DEEP VEINS OF THE LOWER LIMBS

p veins of the lower limbs accompany the arteries and their branches; they have numerous valves (10.178). *Plantar digital veins* arise from plexuses in the plantar regions of the toes, connecting with dorsal digital veins and uniting into four *plantar metatarsal veins*; these run in the intermetatarsal spaces and connect by perforating veins with dorsal veins, then continue to form the *deep plantar venous arch*, accompanying the plantar arterial arch. From this *medial* and *lateral plantar veins* run near the corresponding

Peroneal veins

Posterior tibial veins
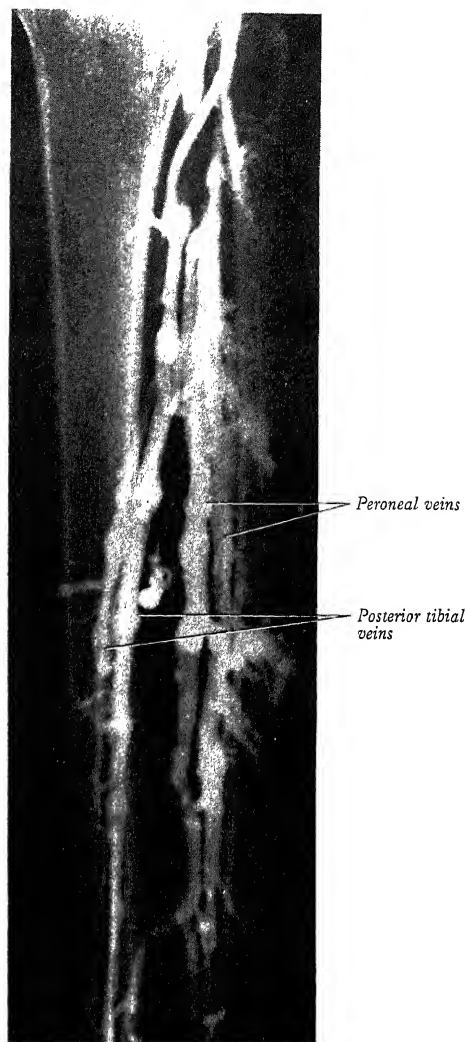
10.178　Venogram of the leg to show the deep veins; the valves are clearly demonstrated. (Supplied by Shaun Gallagher, Guy's Hospital; photography by Sarah Smith.)

arteries and, after communicating with the great and small saphenous veins, form behind the medial malleolus the posterior tibial veins.

Posterior tibial veins. They accompany the posterior tibial artery, receiving veins from sural muscles, especially the venous plexus in the soleus, connections from superficial veins and the *peroneal veins*. The latter, running with their artery, receive rami from the soleus and superficial veins.

Anterior tibial veins. Continuations of the venous companions of the dorsal pedal artery, they leave the extensor region between the tibia and fibula, pass through the proximal end of the interosseous membrane, and unite with the posterior tibial veins to form the *popliteal vein* at the distal border of the popliteus.

Popliteal vein. Ascending through the popliteal fossa to an aperture in adductor magnus, it becomes the femoral vein. Distally it is medial to the artery; between the heads of gastrocnemius it is superficial (dorsal) to it; proximal to the knee joint it is posterolateral. Its tributaries are: the small saphenous vein, veins corresponding to branches of the popliteal artery and muscular veins, including a large one from each head of gastrocnemius. There are usually four valves in the popliteal vein.

Femoral vein. It accompanies its artery, beginning at the adductor opening as the continuation of the popliteal, and ending posterior to the inguinal ligament as the external iliac. In the distal adductor canal, it is posterolateral to the femoral artery; more proximally in

1597

10.180 Venogram showing the veins of the pelvis and groin. The contrast medium has been injected into the bodies of the pubic bones. 1. Injected contrast medium in pubic bones. 2. Internal iliac vein. 3. External iliac vein (faintly outlined). 4. Common iliac vein. 5. Inferior vena cava. 6. Ascending lumbar vein. 7. Obturator vein. 8. Internal pudendal vein. 9. Gluteal vein. (Radiograph supplied by M Lea Thomas.)

INFERIOR

The inferior vena cava conveys blood to the right atrium from all structures below the diaphragm (**10.112**, 179, 181). It is formed by the junction of the common iliac veins anterior to the fifth lumbar vertebral body, a little to its right. It ascends anterior to the vertebral column, to the right of the aorta. Reaching the liver, it is contained in a deep groove on its posterior surface or sometimes in a tunnel completed by a band of liver tissue. It perforates the tendinous part of the diaphragm between its median and right 'leaves' and inclines slightly anteromedially. Passing through the fibrous pericardium and through a posterior inflexion of the serous pericardium it opens into the inferoposterior part of the right atrium. Anterior and left of its atrial orifice is a *semilunar valve of the inferior vena cava*, relatively less prominent in adults, but large and overtly functional in the fetus (p. 1501). The vessel is otherwise devoid of valves.

Relations of the abdominal part. **Anteriorly** the inferior vena cava is overlapped at its commencement by the right common iliac artery and covered, below the horizontal part of the duodenum, by the posterior parietal peritoneum. It is crossed obliquely by the root of the mesentery and its contained vessels and nerves and by the right testicular or ovarian artery. It ascends behind the head of the pancreas and then the superior part of the duodenum, separated from it by the common bile duct and portal vein. Above the duodenum it is again covered by peritoneum of the posterior wall of the epiploic foramen (**12.65**), separating it from the right free border of the lesser omentum and its contents. Above this the liver is anterior.

Posterior are the lower three lumbar vertebral bodies, their intervening 'discs' and the anterior longitudinal ligament, the right psoas major, right sympathetic trunk, and third and fourth right lumbar

arteries; superior to these are the right crus (partially separated by the medial part of the right suprarenal gland and the right coeliac ganglion) and the right renal, suprarenal and inferior phrenic arteries.

Right lateral are the right ureter, the descending part of the duodenum, the medial border of the right kidney and right lobe of the liver. **Left lateral** are the aorta and above this the right crus and caudate lobe.

Relations of the thoracic part. This part of the inferior vena cava is very short, partly inside and partly outside the pericardial sac. The extrapericardial part is separated from the right pleura and lung by the right phrenic nerve. The intrapericardial part is covered, except posteriorly, by inflected serous pericardium.

Surface anatomy. The vein begins in, or just below, the transtubercular plane, its centre 2.5 cm right of the midline; about 2.5 cm wide, it ends behind the sternal end of the sixth right costal cartilage. A band from its lower end to a part of the inguinal ligament centred at a point 1 cm medial to the midinguinal point indicates the common and external iliac veins on each side.

Variations. Numerous anomalies occur and are attributable to arrests or errors in its complex formation. It is sometimes replaced, below the level of the renal veins, by two more or less symmetrical vessels, often associated with the failure of interconnection between the common iliac veins, and due to persistence on the left of a longitudinal channel (usually supra- or subcardinal) which normally disappears in early fetal life (p. 324). In complete visceral transposition, the inferior vena cava is left of the aorta.

Clinical anatomy. Thrombosis of the inferior vena cava leads to oedema of the legs and back, without ascites. Collateral venous circulation is soon established by enlargement of either the superficial or deep veins, or both: the epigastric, circumflex iliac, lateral thoracic, thoraco-epigastric (p. 1597), internal thoracic, posterior intercostal, external pudendal and lumbovertebral anastomotic veins connect it with the superior vena cava; deep connections are made through the azygos, hemiazygos and lumbar veins. Vertebral venous plexuses may also provide effective collateral circulation between the venae cavae (Batson 1957).

Tributaries. These are the common iliac, lumbar, right testicular or ovarian, renal, right suprarenal, inferior phrenic and hepatic veins.

Lumbar veins. Four pairs of lumbar veins collect blood by dorsal tributaries from lumbar muscles and skin, and by abdominal tributaries from the walls of the abdomen, where they connect with the epigastric veins. Near the vertebral column they drain the vertebral plexuses and are connected by the ascending lumbar vein, a longitudinal vessel anterior to the roots of the lumbar transverse processes. The third and fourth lumbar veins pass forward on the sides of the corresponding vertebral bodies to enter the posterior aspect of the inferior vena cava; the left veins pass behind the abdominal aorta and are therefore longer. First and second lumbar veins may join the inferior vena cava, ascending lumbar, or lumbar azygos veins; the first does not usually enter the inferior vena cava: it may turn down to join the second and so open into it indirectly, but more often it ends in the ascending lumbar vein or passes forward over the first lumbar vertebral body to the lumbar azygos vein (p. 1593). The second lumbar vein may join the inferior vena cava at or near the level of the renal veins; sometimes it joins the third lumbar vein or may end in the ascending lumbar. First and second lumbar veins are often connected to each other, to contralateral veins and to right and left lumbar azygos veins by a plexus on the upper lumbar vertebral bodies.

Ascending lumbar vein. It connects the common iliac, iliolumbar and lumbar veins. It lies between psoas major and roots of the lumbar transverse processes. Superiorly it joins the subcostal vein and the vessel so formed turns forward over the twelfth thoracic vertebral body and, passing deep to the crus, ascends as the azygos vein on the right and as the hemiazygos on the left. There is an angle on the vessel as it turns up; it is usually joined here by a small vessel from the back of the inferior vena cava (or left renal vein on the left). This little vein represents the azygos line (p. 325), already described as the lumbar azygos vein (p. 1593). Sometimes the ascending lumbar vein ends in the first lumbar, which then skirts the first lumbar vertebra with the first lumbar artery to join the lumbar azygos vein, the subcostal vein then joining the azygos vein on the right and the hemiazygos on the left.

Testicular veins (**10.112**). They emerge posteriorly from the testis,

Hepatic
vein

renal
vein

Right testicular

Inferior
vena cava

Left renal vein

Lumbar vein
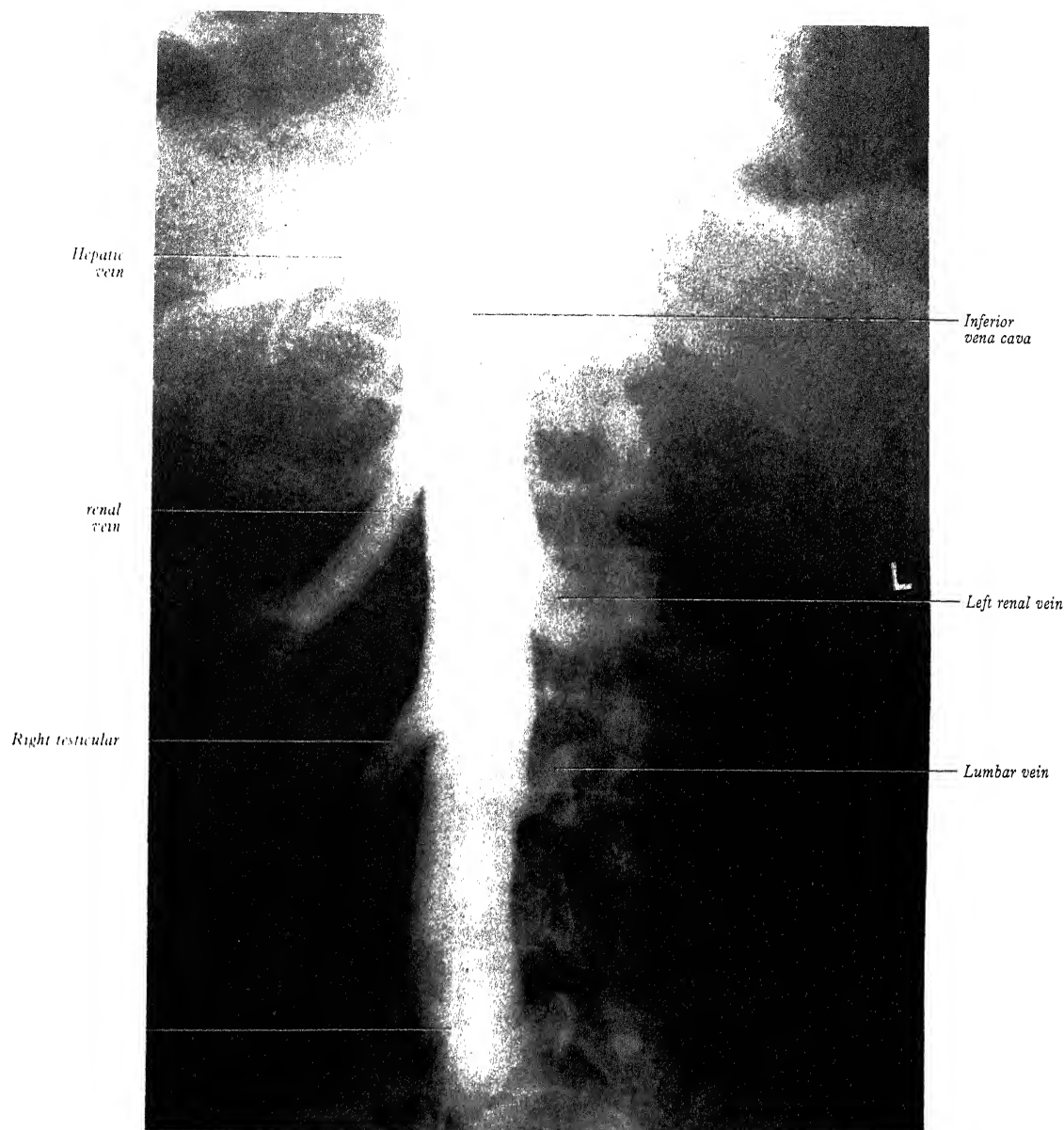
10.181 Inferior vena cavogram in an adult male while performing the Valsalva manoeuvre. (Supplied by Shaun Gallagher, Guy's Hospital; photography by Sarah Smith.)

drain the epididymis and unite to form the pampiniform plexus, a chief component of the spermatic cord, ascending anterior to the ductus deferens. Distal to the superficial inguinal ring the plexus is drained by three or four veins traversing the inguinal canal to the abdomen through the deep inguinal ring; they coalesce into two veins, which ascend anterior to psoas major and ureter, behind the peritoneum, on each side of the testicular artery. These veins join and open into the inferior vena cava on the right at an acute angle just inferior to the level of the renal veins; the left testicular vein opens into the left renal vein at a right angle. The testicular veins contain valves; the left passes behind the lower descending colon and inferior margin of the pancreas and is crossed by the left colic vessels; the right passes behind the terminal ileum and horizontal part of the duodenum and is crossed by the root of the mesentery, ileocolic and right colic vessels.

Clinical anatomy. The testicular veins are frequently varicose; varicocele, which is almost always on the left, is perhaps due to the orthogonal junction of the left testicular and renal veins. There is evidence that the presence of a varicocele raises testicular temperature

and impairs fertility, which is why an operation to correct it is often advised. After removal of a varicocele, venous return is by the small veins of the ductus deferens, cremaster and scrotal tissues.

Ovarian veins. Each of them forms a plexus in the broad ligament near the ovary and uterine tube, communicating with the uterine plexus. Two veins issue from this and ascend across the external iliac artery with the ovarian artery. Their further course is like that of the testicular veins. Valves may occur in them. Like the uterine veins, they are much enlarged in pregnancy.

Renal veins. These large veins lie anterior to the renal arteries and open into the inferior vena cava almost at right angles. The left is three times the right in length (7.5 cm and 2.5 cm); it crosses the posterior abdominal wall posterior to the splenic vein and body of pancreas and, near its end, is anterior to the aorta, just below the origin of the superior mesenteric artery. The left testicular or ovarian vein enters it from below and the left suprarenal vein, usually receiving one of the left inferior phrenic veins, enters it above but nearer the midline. The left renal vein enters the inferior vena cava a little superior to the right. The right renal vein is behind the

descending duodenum and sometimes the lateral part of the head of the pancreas.

Variations. The left renal vein may be double, one vein passing posterior, one anterior to the aorta to join the inferior vena cava, a condition named persistence of the 'renal collar' (p. 325); the anterior may be absent, representing persistence of the posterior limb of the renal collar combined with absence of an intersubcardinal anastomosis.

Clinical anatomy. Because of its close relationship with the aorta, the left renal vein may have to be ligated in the course of, for example, an operation for aneurysm. This seldom results in any harm to the kidney, provided that the ligature is placed to the right of the point of entry of the testicular and suprarenal veins.

Suprarenal veins. They issue from each suprarenal hilum. The right is short, passing directly and horizontally into the posterior aspect of the inferior vena cava; the left descends medially anterior to lateral to the left coeliac ganglion, to pass posterior to the pancreatic body to reach the left renal vein. Whereas the suprarenal glands have a multiple arterial supply from the aorta, phrenic and renal arteries (see p. 1557), venous drainage is by one single drainage on each side. Damage to the suprarenal vein is thus likely to cause an infarction of the gland.

Inferior phrenic veins. Following the corresponding arteries on the inferior diaphragmatic surface, the right ends in the inferior vena cava; the left is often double, one branch ending in the left renal or suprarenal vein, the other passing anterior to the oesophageal opening to join the inferior vena cava.

Hepatic veins. They drain the liver, commencing as *intralobular veins*, draining the sinusoids of liver lobules (p. 1802); these lead to *sublobular veins*, which eventually unite into *hepatic veins*, emerging from the posterior hepatic surface to open at once into the inferior vena cava in its groove on the posterior hepatic surface. Hepatic veins are arranged in upper and lower groups. The **upper** are usually large veins, right, left and middle, the last from the caudate lobe; the **lower**, varying in number, are small and from the right and caudate lobes. The hepatic veins are contiguous with hepatic tissue and have no valves. Large 'accessory' hepatic veins of the lower group, draining a variable volume of the right lobe, have been studied in 93 adult livers by corrosion casts; they are usually single, occasionally double, with an incidence of 15% (Sledzinski & Tyszkiewicz 1975).

HEPATIC PORTAL SYSTEM

The portal system (10.182, 183) includes all the veins draining the abdominal part of the digestive tube (except the lower anal canal but including the abdominal part of the oesophagus) and spleen, pancreas and gallbladder. The portal vein conveys the blood from these viscera to the liver, where it ramifies like an artery, ending in the sinusoids, from which vessels again converge to reach the inferior vena cava via the hepatic veins. The blood therefore passes through two sets of 'exchange' vessels:
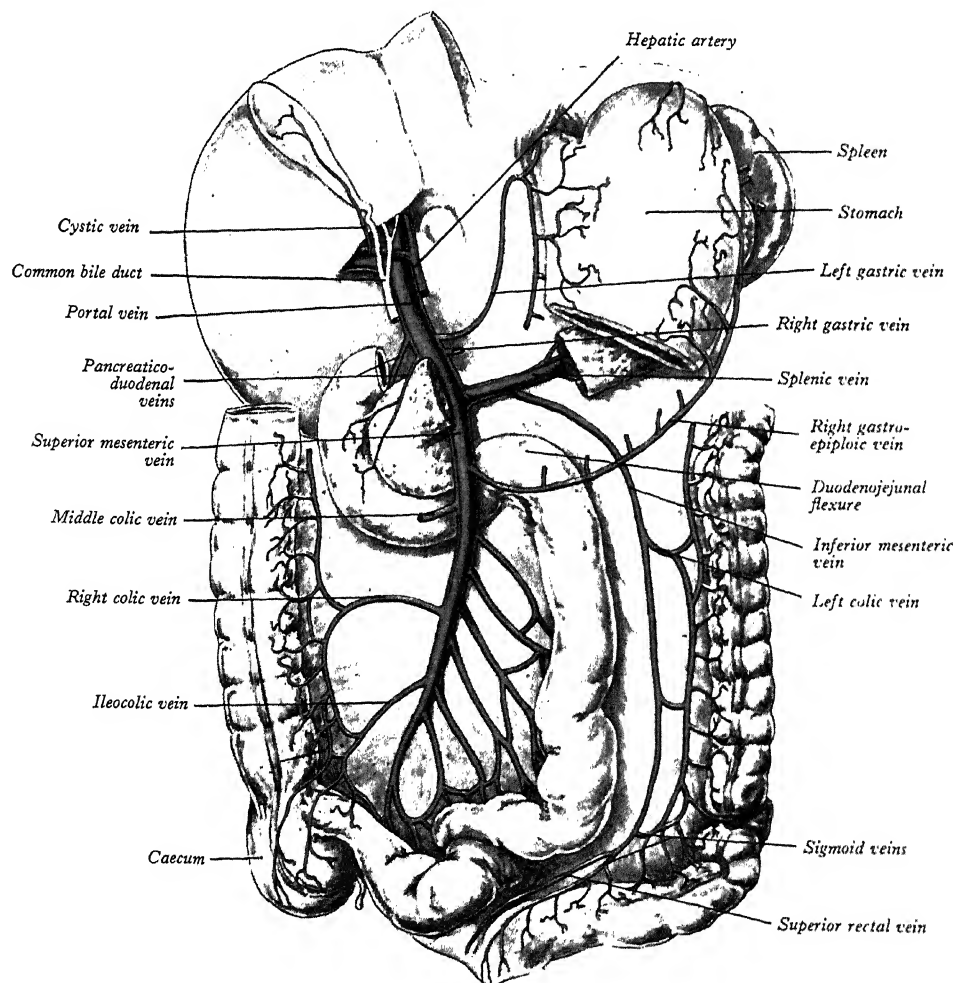
10.182 The portal vein and its tributaries (semi-diagrammatic). Portions of the stomach, pancreas and left lobe of the liver and the transverse colon have been removed.

- capillaries of the digestive tube, spleen, pancreas and gallbladder
- hepatic sinusoids.

In adults, the portal vein and its tributaries have no valves; in fetal life and for a short postnatal period valves are demonstrable in its tributaries; usually they atrophy but some may persist in atrophic form.

Portal vein

About 8 cm long, the portal vein begins at the second lumbar vertebral level from the convergence of superior mesenteric and splenic veins, anterior to the inferior vena cava, posterior to the neck of the pancreas (10.182). It inclines slightly right as it ascends behind the superior part of the duodenum, bile duct and gastroduodenal artery and is here directly anterior to the inferior vena cava; however, it enters the right border of the lesser omentum, ascending anterior to the epiploic foramen to the right end of the porta hepatis, dividing into right and left stems, which accompany the corresponding branches of the hepatic artery into the liver. In the lesser omentum it is posterior to both bile duct and hepatic artery, the former being to the right; it is surrounded by the hepatic nerve plexus and accompanied by many lymph vessels and some lymph nodes. The right branch enters the right hepatic lobe but usually first receives the cystic vein. The left branch, longer but of smaller calibre, branches into caudate, quadrate and left lobes. (See a discussion of hepatic lobation and lobulation, pp. 1796, 1797.) As it enters the left lobe it is joined by para-umbilical veins (p. 1604) and the *ligamentum teres*, which contains the functionless and partly obliterated left umbilical vein. It is connected to the inferior vena cava by the *ligamentum venosum*, a vestige of an obliterated ductus venosus, ascending in a fissure on the liver's posterior aspect (p. 1501). The small extrahepatic section of the left branch, from which veins to the quadrate and left lobes arise, is a persistent part of the left umbilical vein.

Tributaries. These are: splenic, superior mesenteric, left gastric, right gastric, para-umbilical and cystic veins.

Splenic vein

Large and not tortuous, the splenic vein is formed by five or six tributaries from the spleen (10.182, 183). It traverses the lienorenal ligament with the splenic artery and tail of the pancreas, and descends to the right, across the posterior abdominal wall inferior to its artery and posterior to the body of the pancreas (which it grooves), receiving numerous short rami from the gland. It crosses anterior to the left kidney and its hilar structures (or lower pole of the left suprarenal gland), separated from the left sympathetic trunk and crus by the left renal vessels and from the abdominal aorta by the superior mesenteric artery and left renal vein. It ends behind (lodged in) the neck of the pancreas, where it joins the superior mesenteric vein at a right angle to form the portal vein.

Tributaries. These are: short gastric, left gastro-epiploic, pancreatic and inferior mesenteric veins.

Short gastric veins. Four or five of these veins drain the gastric fundus and the left part of its greater curvature, traversing the gastrosplenic ligament to reach the splenic vein or one of its large tributaries.

Left gastro-epiploic vein. This drains both gastric surfaces and the adjacent greater omentum; it runs from right to left along the greater curvature, between the anterior two omental layers, ending in or near the beginning of the splenic vein.

Pancreatic veins. They drain the body and tail of the pancreas. They may be small and many or large and few. The former empty more or less directly into the splenic vein; in the latter case, superior and inferior arcades receive these larger veins, their ultimate drainage being into the splenic (Sow et al 1975, and p. 1795).

Inferior mesenteric vein (10.182). It drains the rectum, and sigmoid and descending parts of the colon. It begins as the superior rectal vein, from the rectal plexus (p. 1598), through which it connects with middle and inferior rectal veins. The superior rectal vein leaves the pelvis and crosses the left common iliac vessels medial to the left ureter with the superior rectal artery, continuing up as the inferior mesenteric vein. This is left of its artery, ascending behind the peritoneum anterior to the left psoas major; it may cross the testicular or ovarian vessels or be medial to them and then passes above, or behind, the duodenojejunal flexure, opening into the splenic vein posterior to the body of the pancreas; sometimes it ends at the union of the splenic and superior mesenteric veins. If a duodenal or paraduodenal fossa exists, the vein is usually in its anterior wall

Catheter in coeliac trunk

Portal vein

Splenic vein

Contrast medium in major calyx of left kidney
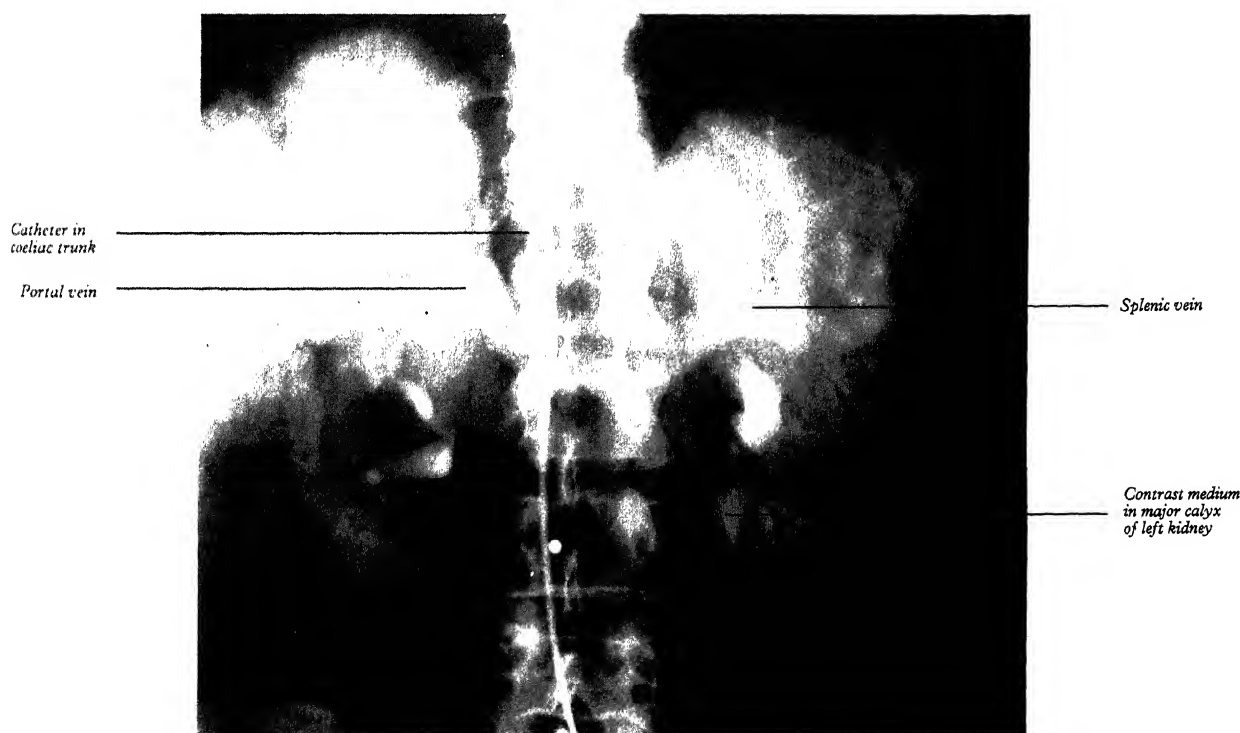
10.183 Venous phase showing the splenic and portal veins after injection of contrast medium into the coeliac trunk.

(p. 1744). Its tributaries are sigmoid veins from the sigmoid colon and the left colic vein from the descending colon and the left colic flexure.

Superior mesenteric vein

The superior mesenteric vein drains the small intestine, caecum and ascending and transverse parts of the colon (10.182). Beginning in the right iliac fossa by the union of tributaries from the terminal ileum, caecum and vermiform appendix, it ascends in the mesentery on the right of the superior mesenteric artery, passing anterior to the right ureter, inferior vena cava, the horizontal part of the duodenum and uncinate process of the pancreas, joining the splenic vein behind its neck to form the portal vein (10.182, 183).

Tributaries. These are: jejunal, ileal, ileocolic, right and middle colic, right gastro-epiploic and pancreaticoduodenal veins.

Right gastro-epiploic vein. This drains the greater omentum and distal part of the stomach, passing right on the gastric greater curvature between the anterior layers of the greater omentum to join the superior mesenteric vein below the neck of the pancreas.

Pancreaticoduodenal veins. They accompany their corresponding arteries: the inferior often joins the right gastro-epiploic vein; the superior usually ascends to the left behind the bile duct to end in the portal vein. Sow et al (1975) have observed anterior intraglandular and posterior venous arcades between the superior and inferior pancreaticoduodenal veins in about 70% of 157 pancreatic corrosion preparations.

Left gastric vein. It drains both gastric surfaces, ascending the lesser curvature to the left in the lesser omentum, to the oesophageal opening, where it receives the oesophageal veins. It then curves back down and to the right behind the omental bursa to end in the portal vein at the upper border of the superior part of the duodenum.

Right gastric vein. This is small and runs to the right along the pyloric section of the lesser curvature in the lesser omentum, ending in the portal vein. It is joined by a prepyloric vein ascending anterior to the pylorus (a surgical guide to the pyloric opening).

Para-umbilical veins. Connecting veins of the anterior abdominal wall and portal vein, they extend along the ligamentum teres and median umbilical ligament (p. 1838). Best developed is one beginning at the umbilicus and running in or on (the hepatic) ligamentum teres in the falciform fold to end in the left branch of the portal vein.

Cystic veins. These veins which drain the gallbladder vary. Those from its superior surface are in areolar tissue between the gallbladder and liver, usually entering the liver through the vesical fossa to join the hepatic veins. The remainder form one or two cystic veins which commonly also enter the liver either directly or after joining the veins draining the hepatic ducts and upper bile duct. Only rarely does a single or double cystic vein drain into the right portal branch.

Clinical anatomy

Portal obstruction may cause ascites, whether obstruction is intra- or extrahepatic. In cirrhosis, radicles of the portal vein are compressed by contraction of the fibrous tissue in their portal canals. In valvular cardiac disease, back-pressure on the hepatic veins, and thus on the whole hepatic circulation, has similar effects. The portal vein may be compressed by hepatic tumours, enlarged lymph nodes in the lesser omentum or carcinoma of the pancreatic head. Portal thrombosis may complicate various conditions. In portal obstruction anastomoses between portal and systemic circulations, which may offer effective collateral circulation, are as follows:

- On the abdominal oesophagus tributaries of the left gastric vein (portal) connect with oesophageal tributaries of the azygos and accessory hemiazygos veins (systemic). Enlargement of these may result in varicosity (oesophageal varices) and even fatal haematemesis (vomiting of blood).
- In the rectal wall opening up of connections between the inferior and middle rectal (systemic) and superior rectal (portal) veins may result in varicosity.
- At the umbilicus, veins running on the ligamentum teres to the left portal branch (p. 1603) connect with the epigastric veins (systemic); enlargement of these connections may produce varicosities of veins radiating from the umbilicus, the caput Medusae.
- Retroperitoneal veins communicate directly with venous radicles of the colon and bare area of the liver.

- Very rarely a patent ductus venosus connects the left branch of the portal vein to the inferior vena cava.

Portal obstruction and variceal haemorrhage were formerly treated by surgical anastomosis between the portal and systemic beds (portocaval or splenorenal anastomosis), but these shunts give rise to severe side-effects due to by-passing the hepatic circulation. They are nowadays best treated by introducing portosystemic connections into the liver substance, by means of an intravascular probe.

In clinical practice access is frequently required to the superior vena cava and the right side of the heart. This may be for monitoring of central venous, intracardiac and pulmonary artery pressures, for long-term feeding, the safe administration of powerful drugs or for passing a cardiac pacing catheter or biopsy forceps. The first successful placement of a central venous catheter was via a peripheral vein but now it is common practice to use one of the larger and more central veins in the upper part of the body, the internal jugular and the subclavian being the most popular. The main advantage of cannulating one of the large central veins lies in the fact that they are almost constant in their position and are available when peripheral veins are thrombosed or collapsed. The following are some of the common venous sites of access.

Cephalic vein. At the wrist this is situated over the dorsolateral aspect of the lower end of the radius (10.168) just proximal to the anatomical snuffbox. This is one of the few constantly sited peripheral veins. However, it is sometimes difficult to negotiate a long catheter past the elbow, and in particular through the clavipectoral fascia where the cephalic vein turns almost through a right angle to join the axillary vein.

Median cubital and basilic veins. These may be identified in the cubital fossa (10.169, 16.10). They are, however, frequently covered by fat, especially in the female, which makes them difficult to see but they are usually palpable especially if the venous return is occluded proximally by a tourniquet. A catheter passed from this site will not always enter the intrathoracic veins though, and may turn upwards into the neck.

Subclavian vein. This is the second most commonly used vein for central venous cannulation, the internal jugular being the most common. There are two percutaneous approaches to the subclavian vein, the supraclavicular and the infraclavicular, though the infraclavicular is more popular.

Infraclavicular approach (10.92). With the patient lying supine and slightly head down to distend the vein, the catheterizing needle is inserted at a point 1 cm below the midpoint of the clavicle. Some prefer a point slightly more medial to this. The needle is initially introduced at a right angle to the skin, but once through is directed towards the posterior aspect of the suprasternal notch which may be made more obvious by placing a finger in it. The needle should enter the vein as it arches over the first rib anterior to scalenus anterior.

Supraclavicular approach (10.92). The most popular skin puncture site is immediately posterior to the clavicle at the lateral edge of the clavicular head of sternocleidomastoid. The needle is initially advanced caudally but then directed medially such that its proximal end (the portion outside the skin) bisects the angle between the clavicle and sternocleidomastoid. The advancing needle is also angled 10° anteriorly towards the retromanubrial area at the level of the sternal angle. Complications arising from attempted subclavian vein cannulation include damage to the brachial plexus, subclavian artery, thoracic duct and, not infrequently, pneumothorax. Fatalities have occurred.

Internal jugular vein (10.154). Percutaneous puncture of the internal jugular vein has become the most popular route for central venous access and it has the advantage of being very safe even when performed by relatively inexperienced operators. It is of particular value when seeking venous access in the patient with circulatory collapse.

There are many approaches to this vein and they may be categorized as high or low, medial, central or lateral. The high approach is at or above the level of the thyroid cartilage, while the low is about

1 cm above the clavicle. The terms medial, central and lateral refer to the puncture site relative to sternocleidomastoid. The high approach is popular because it is very unlikely to cause a pneumothorax.

Most commonly a high, right-sided, medial approach is used in which case the patient should be placed supine and tilted slightly head down to distend the neck veins. The head is turned to the left and the puncture site made just lateral to the upper border of the thyroid cartilage. Some operators like to place one finger on the carotid artery and another on the medial border of sterno-cleidomastoid and to introduce their needle between those two fingers. The needle is then advanced at 45° to the skin aiming at a point three to four fingers' breadth from the right lateral edge of the sternum until venous blood can be aspirated freely.

Femoral vein (10.176). While femoral venous puncture is relatively easy and supplies ready access to the right atrium, the use of this approach is relatively unpopular for long-term cannulation because of a higher incidence of thrombosis and sepsis. It is, however, a useful site for venous sampling in a patient with collapsed veins. For femoral venous cannulation the skin puncture site is approximately 1 cm medial to the femoral artery and just below the inguinal ligament. After skin puncture the needle is advanced with the syringe at an angle of 30° to the skin aiming cephalad.

LYMPHATIC SYSTEM

INTRODUCTION

Dispersed widely in the body are the tissues, fluids and cells concerned in a variety of interrelated functions, including the drainage of tissue fluid formed in the interstitial spaces, the removal by phagocytes of cell debris and foreign matter (p. 1414) and the immune responses of the lymphocytes (p. 1405) and other cells. In part these activities overlap and have a common cellular base with those of the blood vascular system. It is important to distinguish between *lymphatic vessels* or 'lymphatics' which are tubes of endothelial cells, lined externally by some connective tissue, and *lymphoid tissue*, consisting of large aggregates of lymphocytes and associated cells. These cells are in many instances intimately connected with the lymphatic channels, and process or add to their fluid and cellular contents, for example, in lymph nodes and lymphoid nodules. In other cases, lymphoid tissue may be quite separate from lymphatics, for example the spleen, which is concerned with modifying the blood, and the bone marrow and thymus, which produce lymphocytes and other cells to populate the lymphoid tissue elsewhere, with immunologically active cells of different classes. As stated elsewhere, most tissue fluid formed at the arterial ends of capillaries returns to the circulation via their venous ends, but 10–20% of such fluid passes instead into blind-ending lymphatic capillaries, then traverses one or more lymph nodes before returning to the venous system and thus the blood circulation. Before considering the detailed **topography** of lymphatic vessels and lymph nodes, we will consider the **general structure** of lymphatic vessels, lymph nodes, lymphatic nodules, the spleen and the thymus.

LYMPHATIC VESSELS

Lymphatic capillaries form plexuses in tissue spaces which have wider meshes than those of the adjacent blood capillaries. They often begin as dilated tubes with closed ends; the calibres are larger and cross-sectional appearances are less regular than those of blood capillaries, and they lack a basal lamina, though they have numerous vesicles within their cytoplasm, a typical endothelial feature. (See Leak 1984 for a review of lymphatic structure and physiology.) Their endothelium is generally quite permeable to much larger molecules (Allen 1967) and, unlike most blood capillaries, they are readily permeable to colloidal material and larger particles such as cell debris and micro-organisms from tissue spaces, and to cells. When lymph vessels are obstructed, the surrounding tissues become oedematous, i.e. distended with fluid containing much protein. Experiments suggest that the observed absorption of macromolecules and particles is via gaps between endothelial cells or by micropinocytosis through them. Lymph from most tissues is clear and colourless. In contrast, the lymph from the small intestine is dense and milky, due to the presence of lipid globules (*chylomicrons*) derived from fat absorbed by the mucosal epithelium; the terminal vessels in the mucosa of the small intestine are thus known as *lacteals* and the lymph as *chyle*. Lymphatic capillaries, though present in many tissues, are absent from avascular structures (epidermis, hair, nails, cornea, cartilages), and from central nervous tissue and bone marrow; there are very few in the endomysium of skeletal muscles.

Lymphatic capillaries join into larger vessels which pass to local or sometimes more remote lymph nodes. These are arranged largely in *regional groups*, sufficiently regular in position to be named. Each has its region of drainage but a local group is often bypassed. Nodes within a group are often interconnected (Kubik 1974). In general, lymph traverses a series of nodes before reaching a major collecting duct. There are exceptions to this: lymph vessels of the thyroid gland and oesophagus and of the coronary and triangular ligaments of the liver drain directly to the thoracic duct without passing through lymph nodes (Rusznyák et al 1960). The superficial lymphatics of skin adjoin the deep fascia and accompany superficial veins, but some run independently; they have few connections with deep lymphatics. Deep lymphatic trunks usually accompany arteries or veins, almost all reaching either the thoracic duct or the right lymphatic duct (p. 1609), which join the left and right brachiocephalic veins respectively at the root of the neck. Some observers have also reported additional entry points into the venous system through the inferior vena cava and the renal, suprarenal, azygos and iliac veins. As the lymphatic vessels are closely associated with veins in their development (p. 327), such additional connections would not be surprising, although they are likely to be variable. Most lymphatic vessels anastomose freely and across the midline; larger ones have their own plexiform vasa vasorum and nerve fibres. If their walls are acutely infected (lymphangitis) this plexus is congested, marking the paths of superficial vessels by red lines, visible through the skin and tender to the touch.

Lymphatic vessels repair easily and new vessels readily form after damage; these are at first solid cellular sprouts from the endothelial cells of persisting vessels, which later canalize.

Microscopic structure of lymphatic vessels

The wall of lymphatic capillaries consists of a single layer of endothelium, as in haemal capillaries. A continuous basal lamina is often lacking, and specialized intercellular junctions are few. Fenestrae have been demonstrated in subserosal lymphatics, though they are absent in well-fixed subcutaneous lymphatic vessels, except after trauma. Filopodia are frequent on the luminal surfaces and in lacteals similar projections may exist on their external surface. Bundles of extracellular filaments, lymphatic anchoring filaments, 5–10 nm in diameter, extend from the abluminal surface of the endothelial cells to the surrounding stroma. Pericytes are absent (Fraley & Weiss 1961). There is extensive structural variation between lymphatic capillaries in different tissues (Allen 1967; Leak & Burke 1968). As they unite into larger vessels, a thin external connective tissue coat supports the endothelium. Larger collecting trunks (>200 μm) have three layers, similar to those of small veins, although the lumen is considerably larger, relative to wall thickness, than in veins. The tunica intima consists of an endothelium with a thin subendothelial layer of fibrous tissue. The tunica media contains some smooth muscle cells, mostly arranged circumferentially; the tunica adventitia is mainly fibrous connective tissue, with collagen and elastic fibres and occasional nerve fibres (Boggon & Palfrey 1973). Elastic fibres are sparse in the tunica intima, but sufficient to form an external

1605

elastic lamina in the tunica adventitia. Lymphatics differ from small veins in having many more valves, which are semilunar, generally paired and each composed of an extension of the intima. Their edges point in the direction of the current and the vessel wall downstream is expanded into a sinus, giving the vessels a beaded appearance when distended. Valves are important in preventing the backflow of lymph.

The thoracic duct is structurally similar to a medium-sized vein, but the smooth muscle in the tunica media is more prominent and pulsatile movements have been described (see below and p. 1609).

Satiukova and Rassokhina-Volkova (1972) have studied regeneration of lymphatic capillaries in dogs after autotransplantations of hindlegs and lungs; they observed early formation of buds from severed lymphatics in junctional scar tissue, concluding that lymph flow was largely restored.

Movement of lymph

Several factors aid the propulsion of lymph from tissue spaces to lymph nodes and the venous bloodstream:

- 'Filtration pressure' in tissue spaces is generated by filtration of fluid under pressure from blood capillaries.
- Contraction of neighbouring muscles compresses lymph vessels, moving lymph in the directions determined by their valves; extremely little lymph flows in an immobilized limb, whereas flow is increased by either active or passive movements. This fact has been used clinically to diminish dissemination of toxins from infected tissues by immobilization of the relevant regions. Conversely, massage aids the flow of lymph from oedematous regions.
- The pulsation of neighbouring arteries probably compresses adjacent lymphatic vessels, assisting flow in them.
- Respiratory movements and the negative blood pressure in the brachiocephalic veins also promote flow of lymph.
- Smooth musculature in the wall of the lymphatic trunks contracts when sympathetic nerves are stimulated, resulting in reduction of the lumen. Pulsatile contractions in the thoracic duct also occur and, because of the numerous valves along this structure, lymph is forced unidirectionally by this muscular action. However, in markedly dilated vessels valves may become incompetent, allowing retrograde flow, perhaps explaining the observed retrograde spread of some malignant tumours.

Methods of study

Infective material and neoplastic cells often spread from an affected site along lymphatics, and so the details of their pathways from different regions and organs are clinically important. Dissection is not a suitable method for the tracing of these routes because lymphatic vessels are slender and difficult to see. More reliable information has been obtained as follows:

- Experimental injection of substances into organs or tissues of living or dead animals, including man. These enter the lymphatics draining the site of injection and render them and their related lymph nodes visible. The materials most commonly used for this purpose are suspensions of India ink, Neoprene latex or Prussian blue, the latter employed by Jamieson and Dobson (1907–1908, 1910, 1920) in extensive studies of human pathways. In living animals methylene blue and radio-opaque substances, such as lipiodol, have been injected, the latter requiring radiography. Lymphangiography in human subjects, following the injection of lipiodol into the appropriate peripheral lymphatic channels has much increased our knowledge of their routes and is much used diagnostically (Kinmonth 1964; Kinmonth & Taylor 1964).
- Clinical observation of lymph nodes involved in the spread of known inflammatory or malignant disease. However, it must be cautioned that retrograde spread of tumour cells after blockage of a channel limits the reliability of such observations by altering the normal directions of flow.

SPLEEN

1606   (Although part of the cardiovascular system, the spleen is essentially

concerned with immune functions and a filtering of blood. Its structure is dealt with on pages 1437–1442 in the Haemolymphoid system, Section 9.)

TOPOGRAPHY OF LYMPH NODES AND VESSELS

The detailed architecture of lymph nodes and lymphatic vessels is discussed on pages 1431–1432. The structure of lymph nodes is described on pages 1605–1626, that of the spleen on page 1439, and that of the thymus on pages 1424–1429. Lymph nodes occupy fairly well-defined topographical sites, specifically named, each with its area of drainage, interconnections with other nodes or groups and a predominant destination of its efferent vessels. A more detailed consideration of these matters is the concern of the remainder of this chapter; this must be prefaced by a summary, or sometimes a reiteration, of a few general principles. Lymphatic anatomy often appears an almost impossible plethora of topographical names for trunks, groups and subgroups of nodes and their connections. However, an elemental knowledge of general anatomy and a recognition of which of the general principles apply to the major organ systems make many of the difficulties evaporate. It is particularly useful to appreciate the overall pattern present in a particular organ, whole organ system or whole body segment. (Good examples are: the whole subdiaphragmatic alimentary tract, the foregut, the stomach, the tracheobronchopulmonary system, the similarities and contrasting features of the arm and leg and the head and neck as a whole.) These encompass all the main patterns and principles, include all the main terminal lymph trunks whereby lymph is returned to the venous system. The principal groups of lymph nodes towards which lymph converges from wide tissue areas (often through one or more subgroups) and knowledge of which, for many, is mandatory, are clarified. Thereafter, many (but not all) the lesser subgroups, in relation to their formal topographical names, assume a diminished importance in terms of mental retention; nevertheless, their distribution can usually be predicted with confidence. The criteria for the topographical naming of nodes will be mentioned below. Certain general names applied to nodes, although not universally used, often prove useful. Lymph circulating in lymphatic capillaries may be returned to the venous system (ignoring intralymphoidal venular events on a microscopic scale, p. 1432) almost entirely at bilateral sites at or near the junctions between internal jugular and subclavian veins forming right and left brachiocephalic veins; however, their routes vary enormously in length and complexity. In certain exceptional sites (thyroid, oesophagus, dorsal hepatic 'bare areas', p. 1800) the capillaries drain via a radicle of the thoracic duct with no intervening lymph node (an anodal route). In some, a single node provides uninodal routes; the majority of routes are multinodal with sometimes many nodes forming irregular cross-connected chains. In such a chain, the node or group nearest the tissue drained is termed *primary* (outlying, or peripheral), and the last group of the chain, whose efferents form a final uninterrupted principal lymph trunk, is termed *terminal*. Between its primary peripheral and its terminal groups intervening nodes are often segregated into *intermediary* groups; some use the collective term *regional lymph nodes* to include all three groups; others, peripheral and intermediary only. The significance of multinodal pathways is by no means clear; it should be noted that classifications may impose an artificial simplicity on a potentially highly complex monitoring and reacting system. Thus, briefly, a particular node is not one element in a simple chain but, receiving multiple afferent vessels, may, for example, be the primary node for various loci, number three in the chain for other loci, number five for others and so forth. Such considerations, of course, apply to other members of the chain and, summating for the whole chain, there emerges the notion of a system of lymphatic channels and lymphoid stations of great three-dimensional complexity. Differential lymphangiography amply confirms this complexity. This prompts the question: are lymph nodes in general roughly equivalent in their ranges of receptivity (monitoring) and reactivity or do they vary? If variation exists, to what degree? An extreme (and fanciful) extension of this is the possibility of individual nodes, or even sectors of nodes, being unique in their properties, as they unquestionably are in their locations and connections.

TOPOGRAPHICAL NAMING OF LYMPH NODES

Topographical naming of lymph nodes has not followed a single rigid classification; four main frames of reference have been found convenient, and sufficiently clear. These are:

• superficial or deep position
• related vasculature
• related organ's name and architecture
• general topographical location.

Superficial and deep position

Superficial and deep refer to the location of the nodes with respect to the deep fascia. As noted below, many superficial nodes are closely applied to prominent superficial veins. An interesting but unexplained fact is that the upper limb has few superficial nodes and its superficial lymphatic drainage mostly passes directly to deep axillary nodes; in contrast, in the leg the superficial lymphatic drainage passes, almost exclusively, to the large superficial inguinal nodes before continuing to the external iliac nodes.

Relation to vasculature

The majority of nodes and node groups are clustered around or abut a prominent blood vessel or one of its branches; from this (with many notable exceptions) the name of the group is derived. The association assists in recalling the location of the group and in many instances is a strong pointer to the main region of lymph drainage. Examples of superficial nodes associated with veins are: buccal nodes (facial vein), superficial cervical nodes (external jugular vein), anterior cervical nodes (anterior jugular vein), infraclavicular nodes (cephalic vein), supratrochlear nodes (basilic vein), superficial inguinal nodes (great saphenous vein). Deep nodes associated with vessels are so numerous that only a few illustrative examples can be given. The abdominal aorta and common, internal and external iliac arteries are surrounded by nodes. The whole consists of massive chains of nodes, interconnected by lymphatic vessels, predominantly vertically but also obliquely and transversely. Thus, the main groups are named with their vessels: external, internal and common iliac and circumaortic. The latter (often grouped with neighbouring nodes particularly scattered over the inferior vena cava as lumbar nodes) are divided, on sound developmental and lymphodynamic grounds, into a large median ventral aortic group, prominent right and left lateral aortic groups and a sparse retro-aortic group. Details are given in subsequent pages, but a few examples with comments and one possible synthetic approach to study are outlined here. The ventral aortic group aggregates around the three large subdiaphragmatic ventral splanchnic arteries (p. 1548) as coeliac, superior mesenteric and inferior mesenteric groups of nodes, which drain the subdiaphragmatic foregut, midgut and hindgut (and their derivatives), respectively. The foregut provides an excellent framework with respect to its extent and parts (terminal oesophagus, stomach, proximal duodenum); its derivatives (liver, gallbladder and biliary ducts, pancreas and the closely associated spleen); and the mutual disposition of the foregoing and their peritoneal reflexions, omenta and the lesser sac. To this is added the position of the upper abdominal aorta, the coeliac artery, its trifurcation into common hepatic, left gastric and splenic arteries and the courses and main branches of these. Groups of nodes named in relation to these are, for example, left gastric, right gastro-epiploic, hepatic and pancreaticosplenic; other related groups have visceral names, for example paracardial and pyloric (stomach), cystic (gallbladder), 'anterior border of epiploic foramen' (bile duct). The general (interconnected) areas of drainage of these groups are evident and their efferents discharge into the coeliac nodes. The latter also receive the efferents of the superior and inferior mesenteric groups, each of which has received the efferents from systematically named groups, aggregated along their branches, or scattered in the mesentery. The coeliac nodes are thus the terminal group for the whole subdiaphragmatic gut down to midrectal level and for most of the liver, the gallbladder and biliary ducts, pancreas and spleen. Their efferents join to form wide right and left intestinal lymph trunks; these coalesce and also join the right and left lumbar lymph trunks (see below) to form the morphologically variable *abdominal confluence of lymph trunks*, the cranial end of which is the entry to the thoracic duct. Briefly (details p. 1621), the lateral aortic groups drain the tissues supplied by the lateral splanchnic and dorsolateral somatic intersegmental aortic branches; caudally they receive the profuse efferents from the common iliac groups which in turn receive the efferents from the internal and external iliac groups, each with their extensive areas of drainage and further associated outlying groups of nodes. The cranial members of the lateral aortic groups are the terminal nodes for all these tissues; their efferents converge to form the bilateral lumbar lymph trunks which are the other main avenues forming the abdominal confluence of lymph trunks and thence the initial (caudal) end of the thoracic duct. Mention may be made of the nodes associated with drainage of the leg, often misrepresented. Some drainage first involves a limited outlying group of popliteal nodes (near their vessels), then traverses the superficial or deep inguinal nodes which are *intermediary* (not terminal) groups at the limb's root; thereafter the lymph node ascends the chains just described, i.e. via the external and common iliac, the lateral aortic to its upper terminal nodes, then the lumbar lymph trunk, confluence and thoracic duct. (Some deep gluteal lymph follows the internal iliac path to the same destination.) Prominent nodes in the thorax named in relation to vessels are the brachiocephalic group.

Relation to viscera

The names of the visceral lymph nodes are self-evident. Examples already mentioned are the paracardial and pyloric, gastric groups; others are the *superficial* and *deep parotid, submandibular* and *paracolic*. The best examples are concerned with, primarily, the drainage of the lower respiratory tract. Passing from the periphery these are named: *pulmonary* (at major bronchial divisions within the lung), *bronchopulmonary* (or simply 'hilar'), *inferior* and *superior tracheobronchial* (p. 1625) and paratracheal. Their ascending efferents are joined by some from the ipsilateral parasternal, brachiocephalic and posterior mediastinal nodes, forming the right and left bronchomediastinal lymph trunks; these incline over the trachea, then to the ventral aspect of their jugulosubclavian venous junctions. At or in either great vein, near the junction, the trunks usually open independently, but in about one-fifth of individuals the right trunk may join a right lymphatic duct; the left may join the thoracic duct or both may occur.

Names related to general topography

The groups of nodes most easily accessible to clinical palpation have widely used general positional names, which vary considerably in their precision. The relation of many (but not all) their subgroups to prominent blood vessels and their branches is close and this provides a more accurate reference system; in some notable sites this is seldom adopted.

Leg. Outlying *popliteal nodes*—here the name is used indiscriminately with respect to the vessels or the fossa; their palpation is by finger tips probing the fossa along the line of the popliteal vessels with the passively supported limb gradually moved from extension to semiflexion. *Inguinal nodes*: superficial and deep—here inguinal simply implies that they are 'related to the groin'. The deep nodes are few and applied to the medial aspect of the femoral vein; the superficial nodes comprise a lower vertical group clothing the upper great saphenous vein; an upper group parallel to but below the inguinal ligament (related to the superficial circumflex iliac and superficial external pudendal vessels). Palpation is done with the supported limb slightly flexed, abducted and laterally rotated, along a strip 1 cm below the inguinal ligament and a strip 1 cm medial to the central apicobasal line of the femoral triangle.

Arm. Outlying *supratrochlear nodes* (more aptly supra-epicondylar) are adjacent to the basilic vein. Palpation is done along the line of the vein a few centimetres above the elbow joint; many approaches are satisfactory: facing the subject, an elegant approach is to cup the back of the supracubital arm with the appropriate palm; the semiflexed fingers encircle the medial aspect and their aligned tips effortlessly probe along the vein. The *axillary nodes* have subgroups with alternative names; one system applies to their topographical positioning with respect to the 'walls' of the axilla, the second system to their disposition close to the axillary vessels and their branches (especially the veins). These are detailed on page 1613 and will not be pursued here. Palpation demands a systematic approach, exploring each wall of the axilla and any attendant vessels and nodes as

separate manoeuvres. The supported arm is slightly abducted, the examiner facing the lateral aspect of the shoulder; each fold of the axilla is examined with the appropriate hand, semiflexed fingertips invaginating the axillary floor while the thumb grips the fold externally. The fingertips of one or both hands next probe deeply, then down and laterally along the axillary vessels. Finally, the fingers of the pronated hand, inserted deeply, are drawn down the medial wall, i.e. the resistant thoracic wall and serratus anterior. It should be noted that most of the axillary groups are intermediary, with their wide areas of drainage, and the central group is preterminal; only the *apical group* is *terminal*. The latter's efferents form the *subclavian lymph trunk* which approaches and, with variable final morphology, opens at or near its jugulosubclavian junction. The trunk and its opening are on the anterior aspect of the venous walls.

Head and neck. Apart from a few retrovisceral nodes and some deep to the sternocleidomastoid, members of all the nodal groups in the head and neck are clinically palpable when enlarged and all receive regional topographical names. Many of the latter are appropriate and helpful; in the neck, however, the major groups have only the most generalized names, despite their principal relationship to large vessels. (Alternative names based on this merit consideration.) The various groups are detailed elsewhere (p. 1612); thus a simplified overall plan for the head and neck will be mentioned and some group names added to a suggested approach to their clinical examination. The relationship of craniocervical nodes to the deep fascia is discussed subsequently but in some important cases is implied in their names. At the junction of the head with the neck an encircling band extends bilaterally from the chin to the external occipital protuberance, the pericraniocervical ring (often shortened to 'pericervical ring'). Throughout, this encompasses topographically named regional groups with outlying nodes in the face; sequentially the groups are: submental, submandibular (with outlying buccal nodes), retromandibular (outlying parotid), retro-auricular (or mastoid) and occipital. As noted, verbal descriptions of their sites and areas of drainage are given (p. 1612) but in general are obvious from their names. Palpation is carried out from behind the seated subject, using both hands simultaneously, their fingers semiflexed and adducted and thumbs in partial opposition; the fingers explore systematically: the submental triangle, the submandibular glands and triangles (thumbs probing over buccinators), the retromandibular depressions (thumbs over parotids), the upper attachment of sternocleidomastoid and the occipital attachment of trapezius. Palpation now continues along the approximately vertical chains of cervical nodes, superficial and deep. The superficial chains of relatively few, small nodes are associated with the external jugular and anterior jugular veins, the superficial cervical and anterior cervical groups respectively; both drain finally into deep nodes. (These, and unqualified 'deep cervical' are indifferent, non-specific, unhelpful names; the relative precision of vascular or visceral names is preferable.) The main chain of deep cervical nodes is ranged along and embedded in, or in areolar tissue near, the carotid sheath but particularly those aspects surrounding the internal jugular vein. Customarily divided into upper and lower groups, they receive, in addition to their direct areas of drainage, all the efferents from the pericraniocervical ring, efferents from the superficial cervical nodes and efferents from other paravisceral deep nodes (e.g. *retropharyngeal, infrahyoid, prelaryngeal, pretracheal, paratracheal* and *subclavian*). All the lymph from the head and neck finally traverses its ipsilateral *lower deep cervical group*, which is the terminal group. Efferents from the latter converge, forming (right and left) jugular lymph trunks; each descends on its vein to its termination at the jugulosubclavian venous junction.

Lymph node numbers: regional distribution

Accurate, large statistical surveys are not available; the following are pooled data from many limited sources; nevertheless, the overall approximations allow interesting speculation. A normal young adult body contains some 400–450 lymph nodes. Of these the limbs and associated superficial body wall are least well served. The arm and superficial thoraco-abdominal wall (down to the umbilicus) contain about 30 nodes, the leg and superficial buttock, infra-umbilical abdominal wall and perineum only about 20 nodes. (This does not include the iliac and lateral aortic groups which have numerous additional intra-abdominal afferents.) The head and neck carry some 60–70 nodes. The remainder (about 330) is divided between the thorax (deep walls and contents, some 100 nodes or less), and the abdomen and pelvis (deep walls and contents, some 230 nodes or more). Most richly served by nodes is the gastrointestinal tract; also profusely served is the tracheobronchopulmonary tract.

CERVICAL LYMPHOVENOUS PORTALS

Lymph is returned to the venous blood circulation via the right and left lymphovenous portals which are sited at, or near, the junctions of the large internal jugular and subclavian veins forming the even larger right and left brachiocephalic veins. On the right, **three** main lymph trunks converge towards their venous junction; on the left **four** main trunks (three corresponding to the right-sided trunks, but additionally the largest trunk, the thoracic duct). The morphology of the venous termination of these trunks is subject to much variation and the account frequently given in textbooks is a fairly uncommon occurrence, hence the introduction of the generalized term lymphovenous portal.
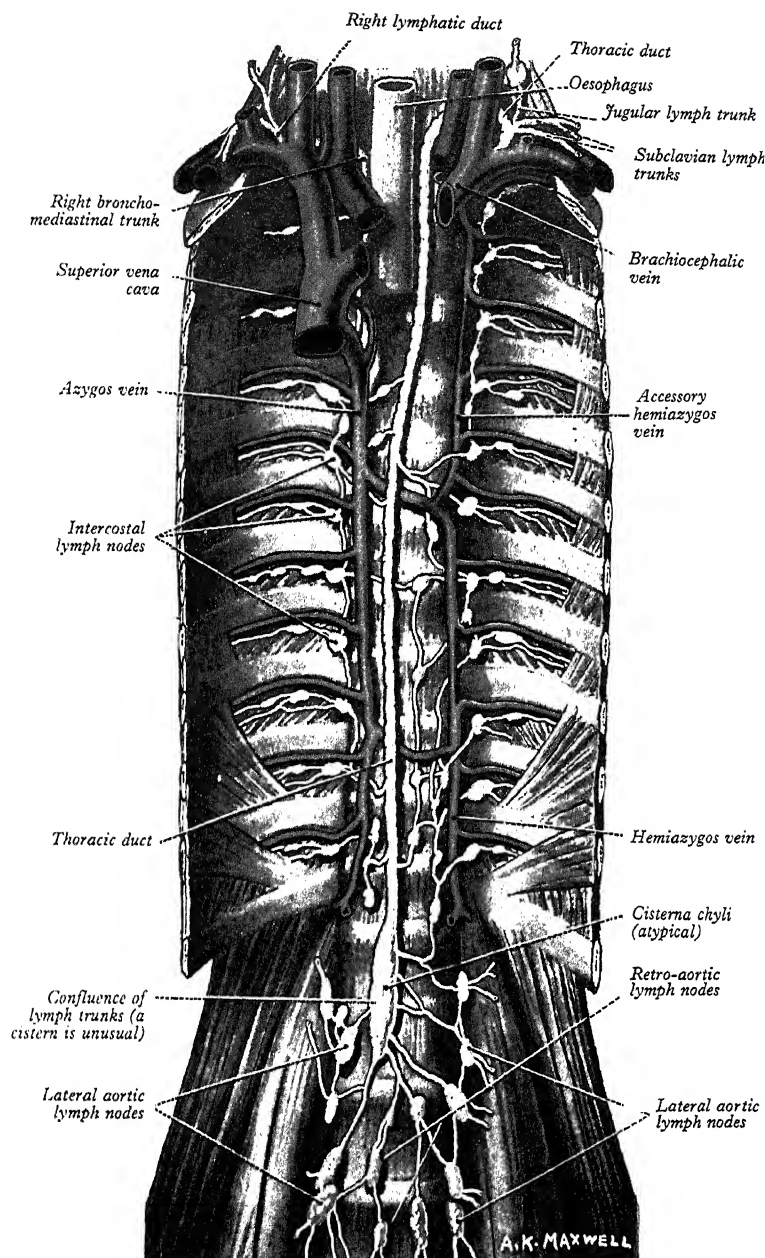
On the right. The three trunks converging here are:

(1) The *right jugular trunk* which extends along the ventrolateral aspect of the internal jugular vein from the terminal lower deep cervical nodes and conveys all the lymph from the right half of the head and neck.

(2) The *right subclavian trunk* from the terminal apical axillary group extending along the axillary and subclavian veins and conveying lymph from the right upper limb and superficial tissues of the right half of the thoraco-abdominal wall down to the umbilicus anteriorly and iliac crest posteriorly (and including much of the mammary gland).

(3) The *right bronchomediastinal trunk* (p. 1625), which ascends over the trachea towards the portal and conveys lymph from the thoracic walls, the right cupola of the diaphragm and subjacent liver, the right lung, bronchi and trachea, the greater part of the 'right heart' (of clinical parlance, not the geometric right half, see p. 1625) and a proportionately small drainage from the thoracic oesophagus.

The *right venous termination* of the three lymphatic trunks is subject to great variation. In the great majority of subjects (80%) they open independently, their orifices clustered on the ventral aspect of the jugulosubclavian junction or in the nearby wall of either of the great veins. In a proportion of these one or more of the trunks may bifurcate (or even trifurcate) preterminally and then have multiple orifices. In one-fifth of subjects only, the three trunks fuse to form a short (1 cm) single right lymphatic duct that inclines across the medial border of scalenus anterior to the ventral aspect of the venous junction, where its orifice is preceded by a bicuspid semilunar valve. An incomplete right lymphatic duct may be present following fusion of, usually, the subclavian and jugular trunks, or any combination of their terminals when divided. In such cases the bronchomediastinal trunk almost invariably opens separately.

Summary. The **right** lymphovenous portal, whatever the final morphology of its trunks, receives lymph from: the right half of the head and neck, the thorax and its contents and superficial tissues of the abdomen and trunk down to the umbilicus and iliac crest, part of the right cupola of the diaphragm and convex surface (only) of the underlying liver and the whole of the right arm. The **left** portal receives much the greater volume of lymph from all the remainder of the body.

On the left. The four trunks converging here on the lymphovenous portal are:

(1) The left jugular trunk, mirroring its right fellow;

(2) the left subclavian trunk, also with a disposition corresponding to its contralateral fellow;

(3) the left bronchomediastinal trunk, similar to the right trunk, but draining more of the heart (the 'left' and part of the 'right hearts' of clinical parlance, p. 1474) and more of the oesophagus;

(4) the thoracic duct, which drains all the extensive remaining regions of the body. At its caudal origin as a continuation of the abdominal confluence of lymphatic trunks (see below), throughout its course and at its cervical venous termination, it is subject to considerable variation.

Right lymphatic duct

Thoracic duct

Oesophagus

Jugular lymph trunk

Subclavian lymph trunks

Right broncho-mediastinal trunk

Brachiocephalic vein

Superior vena cava

Azygos vein

Accessory hemiazygos vein

Intercostal lymph nodes

Thoracic duct

Hemiazygos vein

Cisterna chyli (atypical)

Retro-aortic lymph nodes

Confluence of lymph trunks (a cistern is unusual)

Lateral aortic lymph nodes

Lateral aortic lymph nodes

A.K. MAXWELL

10.184 The thoracic and right lymphatic ducts. The accessory hemiazygos vein is crossing the median plane lower and the hemiazygos higher than usual. Note also the comments concerning the more common course of the azygos vein made in illustration 10.171 and on page 1593. Two features are also uncommon: a single right lymphatic duct (usually two or more trunks open independently); a simple cisterna chyli is infrequent (it is usually a confluence of lymph trunks of varying morphology, page 1610).

THORACIC DUCT (10.184–186)

In adults the thoracic duct including the confluence of lymph trunks (or the cisterna chyli in the small proportion in whom the latter is saccular) is 38–45 cm in length, extending from the second lumbar vertebra to the base of the neck. Starting from the superior pole of the confluence near the lower border of the twelfth thoracic vertebra, it traverses the diaphragm's aortic aperture, then ascends the posterior mediastinum, right of the midline, between the descending thoracic aorta (on its left) and the azygos vein (on its right). **Posterior** to it is the vertebral column (vertebral bodies, symphyses, anterior longitudinal ligament), the right aortic intercostal arteries and terminal segments of the hemiazygos and accessory hemiazygos veins. **Anterior** to it are the diaphragm and oesophagus; a recess of the right pleural cavity may separate the duct and oesophagus. Reaching the level of the fifth thoracic vertebral body it gradually inclines to

the left, enters the superior mediastinum and then ascends to the thoracic inlet along the left border of the oesophagus. In this part of its course the duct is first crossed anteriorly by the aortic arch and it then runs posterior to the left subclavian artery's initial segment, in close contact with the left mediastinal pleura. Passing into the neck it arches laterally at the level of the seventh cervical vertebral transverse process. Its arch rises 3 or 4 cm above the clavicle and curves anterior to the vertebral artery and vein, the left sympathetic trunk, thyrocervical artery or its branches and the left phrenic nerve and medial border of scalenus anterior (but is separated from the nerve and muscle by the prevertebral fascia). The arch passes posterior to: the left common carotid artery, vagus nerve and internal jugular vein. Finally, the duct descends anterior to the arched cervical 'first part' of the left subclavian artery and ends by opening into the junction of the left subclavian and internal jugular veins. However, the duct may open into either of the great veins,

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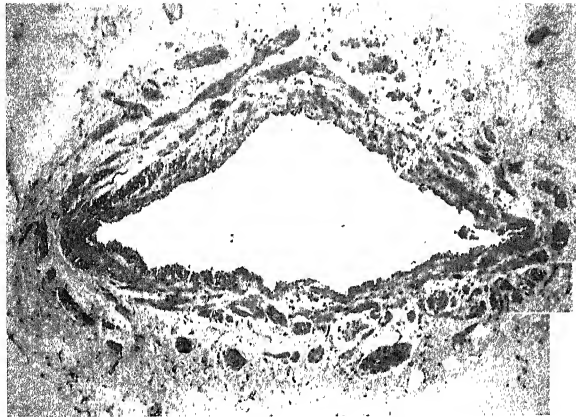
10.185 Transverse section of the thoracic duct showing the fibro-muscular coat (see text). Stained with haematoxylin and eosin. Magnification × 80. (Preparation by Millie Harrison, Department of Anatomy, UMDS, Guy's Campus, London.)

Thoracic duct

5th thoracic vertebra

Thoracic duct

12th thoracic vertebra

10.186 Lymphangiogram showing the entire length of the thoracic duct, approximately 24 hours after injection of lipiodol into a lymphatic vessel on the dorsum of each foot; the cisterna chyli is not evident. (Supplied by G I Verney, Addenbrooke's Hospital, Cambridge; photography by Sarah Smith, Department of Anatomy, UMDS, Guy's Campus, London.)

near the junction, or it may divide into a number of smaller vessels before terminating (see below).

At its abdominal origin the thoracic duct is about 5 mm in diameter but diminishes in calibre at mid-thoracic levels, then in about 50% of subjects is again slightly dilated before its termination. It is slightly sinuous, constricted at intervals and appears varicose. It may divide in its midcourse into two unequal vessels which soon reunite, or into several small branches which form a plexus before continuing as a single duct. At a higher level it occasionally bifurcates, the left branch ending as usual, the right branch diverging to join one of the right lymph trunks or, when present, a right lymphatic duct; the combined vessel usually opens into the right subclavian vein. The thoracic duct has several valves corresponding to sites exposed to pressure. At its termination a bicuspid valve faces into the vein to prevent or reduce reflux of blood. (After death blood regurgitates freely into the duct, which then looks like a vein.)

Termination

Kinnaert (1973) has collected accounts of 529 dissections (49 his own) of the thoracic duct's termination. In 0–4.5% of subjects no thoracic duct appeared on the left. Multiple terminal openings were frequent (10–40%, according to different observers). In Kinnaert's series the preterminal duct was multiple in 66%, but in only 21% were actual terminal openings multiple. Patterns varied greatly in different studies but, in the two largest by Jdanov (1959) and Kinnaert (1973), sites of termination were respectively 48% and 36% internal jugular vein, 9% and 17% subclavian vein, 35% and 34% jugulosubclavian junction. Termination in the left brachiocephalic (innominate) vein occurred in 8% of Jdanov's series, but never in Kinnaert's.
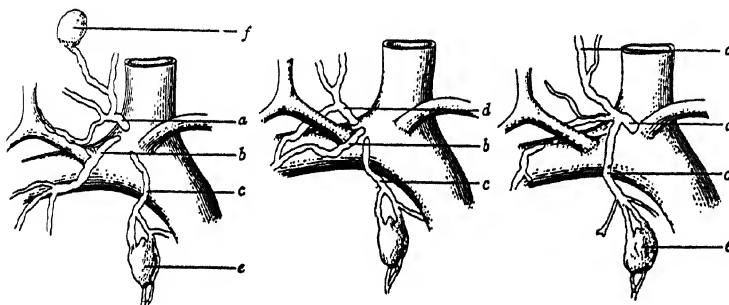
10.187 Variations in the terminal lymph trunks of the right side. a = jugular trunk; b = subclavian trunk; c = bronchomediastinal trunk; d = right lymphatic duct; e = lymph node of parasternal chain; f = lymph node of deep cervical chain. (After Poirier & Charpy.)
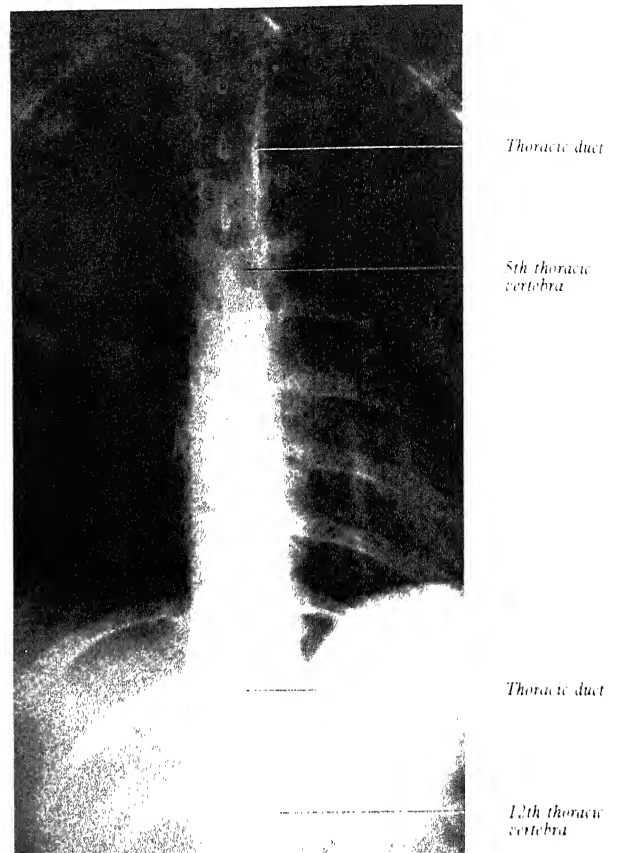
Origin and tributaries

The abdominal origin of the thoracic duct proper is, as stated, situated to the right of the midline at the level of the lower border of the twelfth thoracic vertebral body or the thoracolumbar intervertebral disc. It is the recipient of all the lymph delivered by the four main abdominal lymph trunks, which converge to an elongated arrangement of channels of variable morphology here given the generalized name, *abdominal confluence of lymph trunks*. This may be a simple duct-like extension or be duplicated, triplicated or plexiform; when it is wider than the thoracic duct its interior is sometimes irregular and bilocular or trilocular and may surround intercalated lymph nodes. Only in a small proportion of instances is it a simple, fusiform, saccular dilatation, and the widely-used name *cisterna chyli* should be reserved for these. A published thorough statistical study of the origin of the thoracic duct in mankind appears lacking. Anson (1963) depicted variations: in many a cisterna was absent; when present it was usually multilocular or plexiform; no statistics of incidence were given. Kubik (personal communication 1978) observed a 'cisterna' in 14 of 70 dissections. In only six was it single; it was double in five specimens and trilocular in three. In 56 dissections no cisterna was observed; in half of these collecting trunks formed a direct extension of the thoracic duct; in the other half intercalated nodes (also depicted by Anson 1963) simulated the profiles of cisternae.

The abdominal confluence extends from the caudal beginning of the thoracic duct, vertically, for 5–7 cm anterolateral to the right of the first and second lumbar vertebral bodies (and their intervening disc), and immediately to the right of the abdominal aorta. (Thus its site is overlapped by territories containing upper right lateral aortic lymph nodes and right-sided members of the coeliac and superior mesenteric pre-aortic groups.) The upper two right lumbar

arteries and the right lumbar azygos vein (p. 1593) are between the confluence and the vertebral column. Anterior to it is the medial edge of the right diaphragmatic crus. As mentioned, the confluence (and thence the thoracic duct) receives the right and left lumbar and intestinal lymph trunks. In summary:

(1) The *lumbar trunks* are formed by efferents from lateral aortic lymph nodes. Thus, either directly or after traversing intermediary groups, they carry lymph from: the lower limbs, the full thickness of the pelvic, perineal and infra-umbilical abdominal walls, the deep tissues of most of the supra-umbilical abdominal walls, the pelvic viscera, testes or ovaries, kidneys and suprarenals.

(2) The *intestinal lymph trunks* receive efferents from the coeliac nodes (terminal ventral aortic group) which, after traversing intermediary groups, drain the stomach, intestines (to midrectal levels), pancreas, spleen and the (greater) antero-inferior part of the liver.

Tributaries of the thoracic duct proper (10.187). In summary these are:

• the *confluence of lymph trunks*, just described, the whole outflow of which enters the origin of the thoracic duct
• the bilateral *descending thoracic lymph trunks* from intercostal lymph nodes of the lower six or seven intercostal spaces of both sides which traverse the aortic orifice and join the lateral aspects of the thoracic duct in the abdomen immediately after its origin
• the bilateral *ascending lumbar lymph trunks* from the upper lateral aortic nodes which ascend and pierce their corresponding diaphragmatic crus, then join the the thoracic duct at a variable level within the thorax
• the *upper intercostal trunks* draining the intercostal nodes in the upper five or six left intercostal spaces
• the *mediastinal trunks* draining various nodal groups noted below and providing (amongst other tissues) paths to the thoracic duct
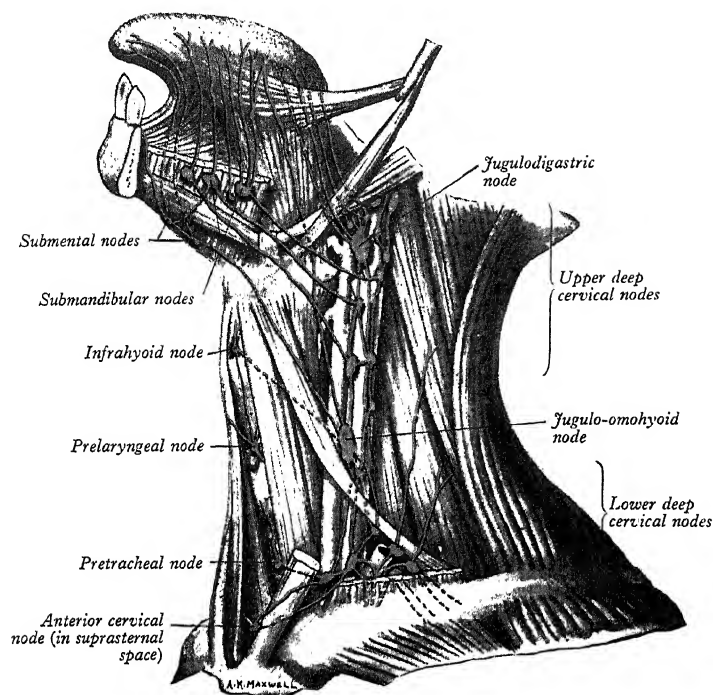
from the convex diaphragmatic aspect of the liver, the diaphragm, the pericardium, heart and oesophagus
• the *left subclavian trunk* which usually joins the thoracic duct, but may open independently into the left subclavian vein
• the *left jugular trunk* which usually joins the thoracic duct, but may open independently into the left internal jugular vein
• the *left bronchomediastinal trunk* which occasionally joins the thoracic duct, usually having an independent venous opening.

Many of the trunks listed above are described as possessing terminal bicuspid valves which possibly prevent reflux of lymph. However, Sapin and Borziak (1974) studied the behaviour of radio-opaque masses in thoracic ducts of 180 cadavers; they found that reflux into several groups of mediastinal and paravertebral groups was usual (under these conditions!).

Nodes in the head and neck comprise a terminal (collecting) group and intermediary, outlying groups. The terminal group is related to the carotid sheath and is named deep cervical. All lymph vessels of the head and neck drain into this, directly from tissues or indirectly through nodes in outlying groups. Efferents of the deep cervical nodes form the *jugular trunk*, which on the right may end in the jugulosubclavian junction or right lymphatic duct; on the left it usually enters the thoracic duct but may join the internal jugular or subclavian vein. In lymphatic drainage the tissues of the head and neck, like other regions, can conveniently be considered as superficial and deep. (See also the generalized arrangement of a peri-craniocervical ring and vertical cervical chains, p. 1608.)

Retro-auricular nodes
Occipital nodes
Superficial cervical nodes
Upper deep cervical nodes
Superficial parotid nodes
Buccal node
Submental nodes
Submandibular nodes
Jugulo-omohyoid node
Lower deep cervical nodes

10.188   The superficial lymph nodes and lymph vessels of the head and neck.
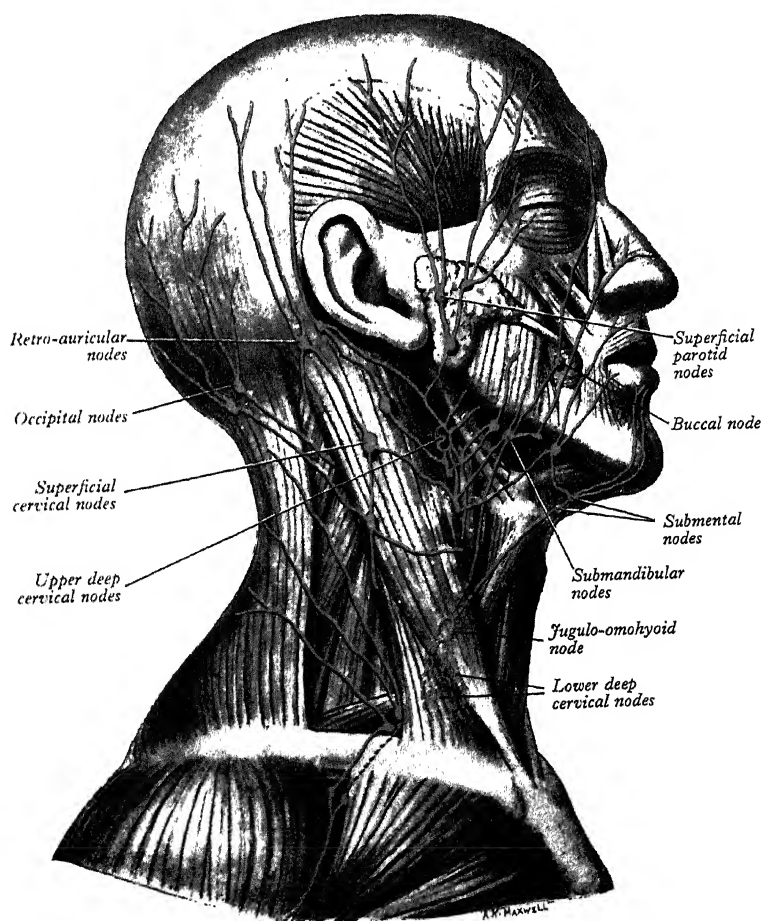
10.189 The lymphatic drainage of the tongue. Removal of the sterno-cleidomastoid has exposed the whole chain of deep cervical lymph nodes. (After Jamieson & Dobson.)

DEEP CERVICAL LYMPHATIC NODES

The deep cervical lymphatic nodes are alongside the carotid sheath; they form superior and inferior groups.

Superior deep cervical nodes (10.188). These adjoin the upper internal jugular vein. Most are deep to the sternocleidomastoid; a few extend beyond it. One subgroup, of one large and several small nodes, is in a triangular region bounded by the posterior belly of the digastric and the facial and internal jugular veins; this jugulodigastric group is concerned specially with lingual drainage. Efferents from the upper deep cervical nodes drain to the lower group or direct to the jugular trunk.

Inferior deep cervical nodes. They are partly deep to the sterno-cleidomastoid, particularly related to the lower internal jugular vein but some, extending also into the subclavian triangle, are closely related to the brachial plexus and subclavian vessels. One node is on or just above the intermediate tendon of omohyoid, the *jugulo-omohyoid node*, and is concerned especially with the tongue (p. 1613). Efferents from this lower group join the jugular lymph trunk.

LYMPHATIC DRAINAGE OF SUPERFICIAL TISSUES OF HEAD AND NECK

Most superficial tissues in the region drain by vessels afferent to local groups of nodes, and efferents from these drain to the deep cervical nodes; but some structures drain directly to deep nodes (10.188). Groups concerned in superficial drainage are:

• in the *head*: occipital, retro-auricular (mastoid), parotid, buccal (facial)
• in the *neck*: submandibular, submental, anterior cervical, super-ficial cervical.

Lymphatic drainage of scalp and ear

Vessels from the frontal region above the root of the nose drain to the submandibular nodes (10.188) and are considered with the face. Vessels from the rest of the forehead, temporal region, upper half of the lateral auricular aspect and anterior wall of the external acoustic meatus drain to the superficial parotid nodes, just anterior to the tragus, on or deep to the parotid fascia. These also drain lateral

vessels from the eyelids and skin of the zygomatic region. Their efferent vessels pass to the upper deep cervical nodes. A strip of scalp above the auricle, the upper half of the auricle's cranial aspect and margin and the posterior wall of the external acoustic meatus all drain to the upper deep cervical and retro-auricular nodes.

The *retro-auricular nodes* (10.188), superficial to the mastoid attachment of sternocleidomastoid and deep to auricularis posterior, drain to the upper deep cervical nodes. The auricular lobule, floor of the meatus and skin over the mandibular angle and lower parotid region are drained to the superficial cervical or upper deep cervical nodes. *Superficial cervical nodes* spread along the external jugular vein superficial to sternocleidomastoid, some efferents passing round the anterior border of sternocleidomastoid to the upper deep cervical nodes; others follow the external jugular vein to the lower deep cervical nodes in the subclavian triangle.

The occipital scalp is drained partly to the occipital nodes, partly by a vessel along the posterior border of sternocleidomastoid to the lower deep cervical nodes. Occipital nodes are occasionally in the superior angle of the posterior triangle but commonly superficial to the upper attachment of trapezius.

Lymphatic drainage of face

Lymph vessels draining the eyelids and conjunctiva commence in a subcutaneous plexus and a deep plexus around the tarsal plates; these communicate and medial and lateral vessels drain from them. Lateral vessels drain the whole thickness of both lids, except their medial parts and all the conjunctiva. They pass from the lateral commissure to the superficial parotid nodes and deep nodes embed-ded in the parotid gland, also receiving lymph from the middle ear (see below). The medial palpebral vessels drain the whole thickness of the medial parts of the lids and caruncula lacrimalis. Following the facial vein, they end in submandibular nodes.

There are usually three *submandibular nodes* (10.188, 189), internal to the deep cervical fascia in the submandibular triangle. There is one at the anterior pole of the submandibular gland, and two flanking the facial artery as it reaches the mandible. Other nodes are often embedded in the gland or deep to it. Submandibular nodes drain a wide area, including vessels from the submental, buccal and lingual groups of nodes; their efferents pass to the upper and lower deep cervical nodes. The external nose, cheeks, upper lip and lateral parts of the lower lip drain directly to the submandibular nodes; the afferent vessels may have a few *buccal nodes* along their course and near the facial vein. The mucous membrane of lips and cheeks also drains to the submandibular nodes. The lateral part of the cheek drains to the parotid nodes. The skin over the nasal radix and central forehead drains partly to the parotid nodes, partly to the submandibular.

The central part of the lower lip, buccal floor and lingual apex drain to the *submental nodes*, which are on the mylohyoid between the anterior bellies of the digastric muscles (10.189). They receive afferents from **both** sides, some decussating across the chin; their efferents pass to the submandibular and jugulo-omohyoid nodes.

Lymphatic drainage of neck

Many vessels draining the superficial cervical tissues skirt the borders of sternocleidomastoid to the superior or inferior deep cervical nodes; but some pass over sternocleidomastoid and the posterior triangle to the superficial cervical and occipital nodes. Lymph from the superior region of the anterior triangle drains to the submandibular and submental nodes; vessels from the anterior cervical skin inferior to the hyoid bone pass to the anterior cervical lymph nodes near the anterior jugular veins; their efferents go to the deep cervical nodes of both sides, including the infrahyoid, prelaryngeal and pretracheal groups (see below). An anterior cervical node often occupies the suprasternal space (p. 804).

LYMPHATIC DRAINAGE OF DEEP TISSUES OF HEAD AND NECK

Tissues of the head and neck internal to the deep fascia drain to the deep cervical nodes directly or through outlying groups which include, in addition to those named above: the retropharyngeal, paratracheal, lingual, infrahyoid, prelaryngeal and pretracheal groups.

Retropharyngeal nodes. These comprise a median and two lateral groups, the latter anterior to the lateral atlantal masses along the lateral borders of the longi capitis. All lie between the pharyngeal and prevertebral fasciae, receiving afferents from the nasopharynx, pharyngotympanic tube and atlanto-occipital and atlanto-axial joints. They drain to the upper deep cervical nodes.

Paratracheal nodes. They flank both trachea and oesophagus along the recurrent laryngeal nerves. Efferents pass to the corresponding deep cervical nodes.

Infrahyoid, prelaryngeal and pretracheal nodes. Found beneath the deep cervical fascia, they drain afferents from the anterior cervical nodes, their efferents joining the deep cervical nodes. The infrahyoid nodes are anterior to the thyrohyoid membrane, prelaryngeal on the conus elasticus and cricovocal membrane, pretracheal anterior to the trachea near the inferior thyroid veins.

Lingual nodes. Small and inconstant, they are situated on the external surface of hyoglossus and also between the genioglossi. They drain to the upper deep cervical nodes.

Lymphatic drainage of nasal cavity, nasopharynx and middle ear

Lymphatics of the nasal cavity can be injected from the subarachnoid space, via communications along the olfactory nerves. Lymph vessels from its anterior region pass superficially to join those of the external nasal skin, ending in the submandibular nodes. The rest of the cavity, paranasal sinuses, nasopharynx and pharyngeal end of the auditory tube drain to the upper deep cervical nodes, directly or through the retropharyngeal nodes. The posterior nasal floor probably drains to the parotid nodes.

Lymphatic vessels of the tympanic and antral mucosae drain to the parotid or upper deep cervical lymph nodes; vessels of the tympanic end of the auditory tube probably end in the deep cervical nodes; its vessels have been identified in the submucosa by injection and electron microscopy (Pulec et al 1975).

Lymphatic drainage of larynx, trachea and thyroid gland

Laryngeal lymphatic vessels form superior and inferior groups; on the lateral wall they are distinct, their division being at the level of the vocal fold; the two sets anastomose on the posterior wall. Superior vessels pierce the thyrohyoid membrane to accompany the superior laryngeal vessels, ending in the superior deep cervical nodes; inferior vessels pass between the cricoid cartilage and the first tracheal ring to the inferior deep cervical lymph nodes, or pierce the cricovocal membrane to reach the pretracheal and prelaryngeal nodes.

A dense network of lymph vessels exists in the tracheal wall; its cervical part drains to the pretracheal and paratracheal nodes, or directly to the inferior deep cervical nodes.

Thyroid lymphatic vessels communicate with the tracheal plexus, passing to the prelaryngeal nodes just above the thyroid isthmus and to the pretracheal and paratracheal nodes; some may drain into the brachiocephalic nodes, related to the thymus in the superior mediastinum. Laterally, the gland is drained by vessels along the superior thyroid veins to the deep cervical nodes. Some thyroid lymphatics may drain directly, with no intervening node, to the thoracic duct (p. 1609).

Lymphatic drainage of mouth, teeth, tonsil and tongue

Mouth. Gingival vessels drain to the submandibular nodes; those of the hard palate continue anteriorly into the superior gingival channels but also run back to pierce the superior constrictor, ending in the superior deep cervical and retropharyngeal nodes; from the soft palate they pass posterolaterally partly to the retropharyngeal, partly to the superior deep cervical nodes. The anterior part of the floor of the mouth drains to the lower nodes of the upper deep cervical group, either directly or via the submental nodes; vessels from the remainder of the floor drain to the submandibular and superior deep cervical nodes.

Teeth. Dental lymphatics pass to the submandibular and deep cervical nodes.

Tonsil. Vessels from the tonsil pierce the buccopharyngeal fascia and superior constrictor to pass between the stylohyoid muscle and the internal jugular vein to the superior deep cervical nodes. Most end in the jugulodigastric nodes; occasionally one or two vessels run

to the small nodes on the lateral aspect of the internal jugular vein, deep or medial to sternocleidomastoid.

Tongue (10.189). A lymphatic plexus in the lingual mucosa is continuous with an intramuscular plexus. The anterior lingual region drains into the marginal and central vessels and behind the vallate papillae into the dorsal lymph vessels.

Vessels. These are divided into marginal, central and dorsal.

Marginal vessels. They come from the lingual apex and frenular region and descend under the mucosa to widely distributed nodes:

- Some pierce the mylohyoid in contact with the mandibular periosteum to enter the submental nodes and also pass anterior to the hyoid bone to the jugulo-omohyoid node. Vessels arising in the plexus on one side may cross under the frenulum to end in the contralateral nodes; efferent vessels of submental nodes, which are median, pass to both sides.

- Some vessels pierce the mylohyoid to enter the anterior or middle submandibular node.

- Some pass inferior to the sublingual gland and, accompanying the companion vein of the hypoglossal nerve, end in jugulo-digastric nodes; one often descends further, superficial or deep to the intermediate tendon of the digastric, to reach the jugulo-omohyoid node.

- Some vessels from the lateral lingual margin cross the sublingual gland, pierce the mylohyoid and end in the submandibular nodes; others end in the jugulodigastric or jugulo-omohyoid nodes. Vessels from the posterior part of the lingual margin traverse the pharyngeal wall to the jugulodigastric lymph nodes.

Central vessels. The regions of the lingual surface draining into the marginal or central vessels are not distinct. Central vessels descend between the genioglossi, some turning laterally through the muscles; but most pass between them and diverge to the right or left, following the lingual veins to the deep cervical nodes, especially the jugulodigastric and jugulo-omohyoid. Some pierce the mylohyoid to enter the submandibular nodes.

Dorsal vessels. Vessels draining the region of the vallate papillae and behind them run postero-inferiorly, some near the median plane to both sides. They turn laterally to join the marginal vessels; all pierce the pharyngeal wall, passing around the external carotid arteries to reach the jugulodigastric and jugulo-omohyoid lymph nodes. One may descend posterior to the hyoid bone, perforating the thyrohyoid membrane to end in the jugulo-omohyoid node.

Lymphatic drainage of pharynx and cervical part of the oesophagus

Collecting vessels from the pharynx and cervical oesophagus pass to the deep cervical nodes, either directly or through the retropharyngeal or paratracheal nodes. From the epiglottic region lymph vessels run to the infrahyoid nodes.

LYMPHATIC DRAINAGE OF UPPER LIMBS

All lymphatic vessels from the upper limb (and superficial tissues of a wide area of the side of the trunk) drain to the axillary nodes, either directly or (a few) through a more peripheral group. Vessels internal to the deep fascia follow the principal vascular bundles; superficial vessels, except in the hand and dorsum of the forearm, converge towards the superficial veins, which they accompany.

Axillary nodes

Axillary nodes drain the whole upper limb and areas of the trunk indicated, are large, vary from 20 to 30 in number, and may be divided into five not wholly distinct groups (10.191, 193). Four of these groups are intermediary; only the apical group is terminal.

(1) A *lateral group* (10.190, 191, 193) of four to six nodes is posteromedial to the axillary vein, its afferents draining the whole limb except the vessels accompanying the cephalic vein. Efferent vessels pass partly to the central and apical axillary groups, partly to the inferior deep cervical nodes.

(2) An *anterior* or *pectoral group* of four or five nodes spreads along the inferior border of pectoralis minor near the lateral thoracic
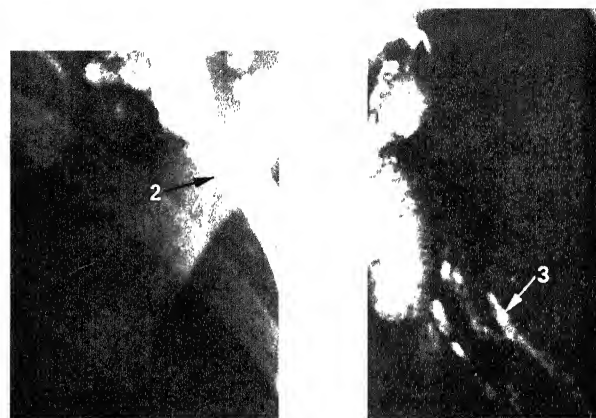
10.190 The lymphatic drainage of the superficial tissues of the upper limb: anterior aspect (semi-diagrammatic).

10.191 Normal axillary lymphangiogram, four days after injection of ultrafluid lipiodol into a lymph vessel on the dorsum of the hand. 1 = lateral group of lymph nodes; 2 = pectoral group of lymph nodes; 3 = brachial lymph vessels. (Supplied by J B Kinmonth.)

vessels. Its afferents drain the skin and muscles of the supra-umbilical anterolateral body wall and mammary gland (centrolateral part, p. 1615); efferents pass partly to the central and partly to the apical axillary nodes.

(3) A *posterior* or *subscapular group* of six or seven nodes is deployed on the posterior axillary wall's inferior margin, along the subscapular vessels. Afferents drain the skin and superficial muscles of the inferior posterior region of the neck and the dorsal aspect of the trunk down to the iliac crest; efferents pass to the apical and central axillary nodes.

(4) A *central group* of three or four large nodes embedded in axillary fat receives afferents from all preceding groups: its efferents drain to the apical nodes.

(5) An *apical group* of six to twelve nodes is partly posterior to the superior part of pectoralis minor and partly above its superior border, extending to the axilla's apex medial to the axillary vein. The only direct territorial afferents are those with the cephalic vein and some draining the mammary gland (upper peripheral region); but the group drains all other axillary nodes. Its efferents unite as the subclavian trunk, draining directly to the jugulosubclavian venous junction, the subclavian vein, or to the jugular lymphatic trunk or on occasion to a right lymphatic duct; the left trunk usually ends in

the thoracic duct. A few efferents from apical nodes usually reach the inferior deep cervical nodes.

Extra-axillary outlying groups in the upper limb are few, comprising: supratrochlear, infraclavicular (both interposed in superficial routes) and isolated nodes occasionally appearing along principal blood vessels.

(1) *Supratrochlear nodes*, only one or two, are superficial to the deep fascia proximal to the medial epicondyle and medial to the basilic vein; their efferents accompany the vein to join the deep lymph vessels.

(2) *Infraclavicular nodes* appear beside the cephalic vein, one or two in the groove between the pectoralis major and deltoid, just inferior to the clavicle; efferents pass through the clavipectoral fascia to apical axillary nodes; more rarely some pass anterior to the clavicle to reach the inferior deep cervical (supraclavicular) nodes.

(3) Small isolated nodes sometimes occur along the radial, ulnar and interosseous vessels, in the cubital fossa near the bifurcation of the brachial artery, or in the arm medial to the brachial vessels.

Lymphatic drainage of superficial tissues

Superficial lymphatic vessels in the upper limb begin in the cutaneous plexuses. In the hand, the palmar plexus is denser. Digital plexuses are drained along the digital borders to their webs, where they join the distal palmar vessels which pass back to the hand's dorsal aspect (10.190, 192). The proximal palm drains towards the carpus, medially by vessels along its ulnar border and laterally to join those of the thumb. Several vessels from the central palmar plexus form a trunk winding round the second metacarpal bone to join the dorsal vessels from the index and thumb. In the forearm and arm, superficial vessels run with superficial veins. Collecting vessels from the hand pass into the forearm on all carpal aspects. Dorsal vessels, after running proximally in parallel, curve successively round the borders of the limb to join the ventral vessels (10.192). Anterior carpal vessels traverse the forearm parallel with the median vein of the forearm to the cubital region, proximal to which they follow the medial border of the biceps, then pierce the deep fascia at the anterior axillary fold and end in the lateral axillary lymph nodes.

Vessels which are lateral in the forearm follow the cephalic vein

to the level of the tendon of the deltoid, where most incline medially to reach the lateral axillary nodes; a few, however, continue with the vein to the infraclavicular nodes. These lateral vessels receive those curving round the lateral border from the limb's dorsal aspect. Vessels which are medial in the forearm follow the basilic vein. Proximal to the elbow some end in supratrochlear lymph nodes, whose efferents, with the medial vessels which have bypassed them, pierce the deep fascia with the basilic vein to end in the lateral axillary nodes or deep lymphatic vessels. They are joined by vessels curving round the medial border of the limb.

Collecting vessels from the deltoid region pass round the anterior and posterior axillary fold to end in the axillary nodes. The scapular skin drains either to subscapular axillary nodes or by channels following the transverse cervical vessels to the inferior deep cervical nodes.

Lymphatic drainage of deep tissues of upper limb

Deep lymph vessels follow the main neurovascular bundles (radial, ulnar, interosseous and brachial) to the lateral axillary nodes. They are less numerous than the superficial vessels, communicating with them at intervals. A few lymph nodes occur along them. Scapular muscles drain mainly to the subscapular axillary nodes and pectoral muscles to the pectoral, central and apical nodes.

Mammary lymphatic drainage

Lymph vessels of the mammary gland start in a plexus in the interlobular connective tissue and walls of the lactiferous ducts, communicating with a cutaneous subareolar plexus around the nipple (10.193). The gland is also said to connect with a plexus of minute vessels on the subjacent deep fascia; this connection plays little part in normal lymphatic drainage nor in early spread of carcinoma (Turner-Warwick 1959). It offers an alternative route when the usual pathways are obstructed. Efferent vessels directly from the gland pass round the anterior axillary border through the axillary fascia to the pectoral lymph nodes; some may pass directly to the subscapular nodes. From the gland's superior region a few vessels pass to the apical axillary nodes, sometimes interrupted in the infraclavicular nodes or in small, inconstant interpectoral nodes. Axillary nodes receive more than 75% of lymph from the gland, the remainder largely draining to parasternal nodes from the medial and lateral parts of the organ; these vessels accompany perforating branches of the internal thoracic artery. Lymphatic vessels occasionally follow lateral cutaneous branches of the posterior intercostal arteries to the intercostal nodes. Cutaneous lymphatic drainage is described on page 1624.

Clinical anatomy

Enlargement of the axillary nodes is frequent in malignant disease and infective processes affecting the upper back and shoulder, the front of the chest and mammary gland, upper anterolateral abdominal wall or upper limb (palpation, see p. 1607). In operations for mammary carcinoma, pectoralis major, its deep fascia and surrounding muscles are usually removed en bloc because of the wide ramifications of its lymphatics. Axillary nodes, the sternocostal head of pectoralis major and frequently pectoralis minor are also removed, to ensure complete removal of the affected lymphatics and nodes. (Some surgeons, relying on more effective diagnostic techniques, now advocate less radical extirpation.)

LYMPHATIC DRAINAGE OF LOWER

Most lymph from the lower limb traverses a large intermediary inguinal group of nodes; some may first traverse a few more peripheral intermediary nodes, however, these are less numerous in the lower limb than elsewhere. The inguinal nodes are superficial and deep to the deep fascia. Although commonly stated as such, the inguinal nodes are not the terminal group for the lower limb; from them the lymph traverses the external and common iliac groups, followed by the lateral aortic group. Deep gluteal lymph reaches the same group through the internal and common iliac chains. The upper lateral aortic nodes are terminal, forming bilateral lumbar

10.192   The lymphatic drainage of the superficial tissues of the upper limb: posterior aspect (semi-diagrammatic).

trunks which discharge lymph into the confluence of trunks (p. 1611) and thence the thoracic duct.

Superficial inguinal nodes

The superficial inguinal nodes form proximal and distal groups (10.194A, 195–197). The proximal is usually of five or six nodes just distal to the inguinal ligament. Its lateral members receive afferent vessels from the gluteal region and adjoining infra-umbilical anterior abdominal wall. Medial members receive superficial vessels from: the external genitalia (including the inferior vagina), inferior anal canal and perianal region, adjoining abdominal wall, umbilicus and the uterine vessels accompanying the round ligament. The distal group, usually four or five, along the termination of the great saphenous vein, receives all superficial vessels of the lower limb, except those from the calf's posterolateral region. All superficial inguinal nodes drain to the external iliac nodes, some via the femoral canal and others anterior or lateral to the femoral vessels. Numerous vessels interconnect individual nodes.

Deep inguinal nodes

The deep inguinal nodes vary from one to three, situated medial to the femoral vein. One is just distal to the saphenofemoral junction, one in the femoral canal; the most proximal one lies laterally in the femoral ring; the middle node is the most inconstant and the proximal node is often absent. All receive deep lymphatics accompanying the femoral vessels, lymph vessels from the glans penis (or clitoris) and   1615
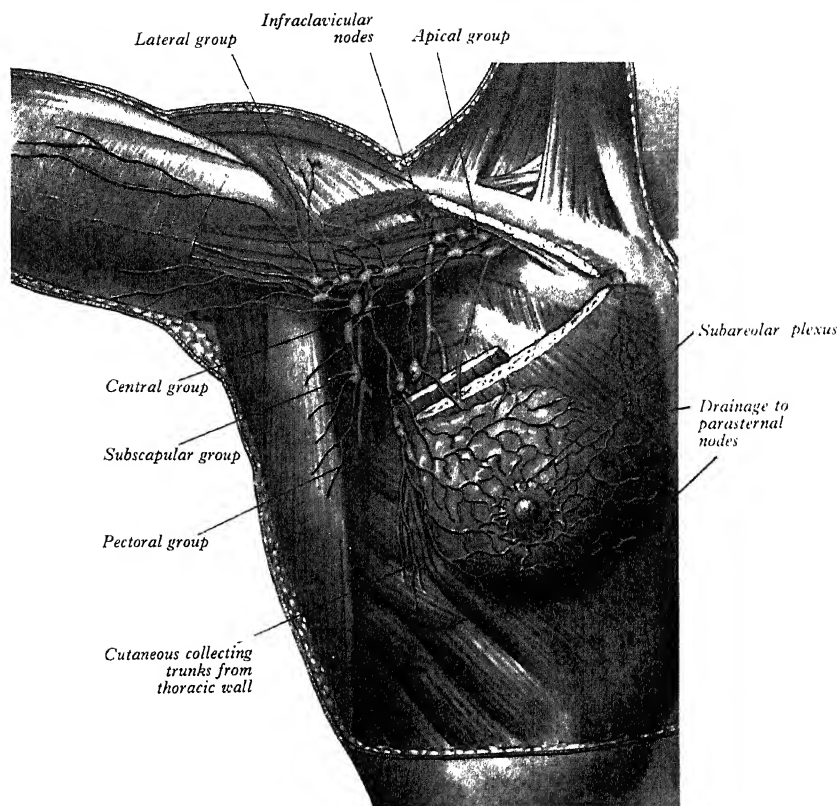
10.193 Lymph vessels of the mammary gland and the axillary lymph nodes.

a few efferents from the superficial inguinal nodes; their own efferents traverse the femoral canal to the external iliac nodes.

Peripheral nodes are few and are all deeply sited. Except for one sometimes proximal on the interosseous membrane near the anterior tibial vessels, they occur only in the popliteal fossa.

Popliteal lymph nodes

The small popliteal lymph nodes, usually six, are embedded in popliteal fat (**10.194B**). One, near the end of the small saphenous vein, drains the superficial region served by the vein. Another is between popliteal artery and posterior aspect of the knee joint, receiving direct vessels from the knee joint and those accompanying the genicular arteries. The remainder flank the popliteal vessels, receiving trunks accompanying the anterior and posterior tibial vessels. Popliteal efferents ascend close to the femoral vessels to reach the deep inguinal nodes but some may accompany the great saphenous vein to the superficial inguinal nodes.

Clinical anatomy. Inflammation of the popliteal nodes is often due to lateral lesions of the heel. Superficial inguinal nodes are frequently enlarged in disease or injury in their region of drainage (palpation, see p. 1607). Thus in malignant or infective disease of the prepuce, penis, labia majora, scrotum, abscess in the perineum, anus and lower vagina or in diseases affecting skin and superficial structures in these regions, or the infra-umbilical part of the abdominal wall, the gluteal region: in all these the proximal inguinal nodes are almost invariably affected, the distal group being implicated only in disease or injury of the limb.

Lymphatic drainage of superficial tissues in lower limbs

The superficial lymph vessels begin in subcutaneous plexuses. Collecting vessels leave the foot medially, along the great saphenous vein and, laterally, with the small saphenous.

Medial vessels are larger, more numerous and begin on the tibial side of the foot's dorsum, some ascending anterior and others posterior to the medial malleolus; thereafter both converge on the great saphenous vein and accompany it to the distal superficial inguinal nodes. *Lateral vessels* begin on the fibular side, some crossing anteriorly in the leg to join the medial vessels and so to the distal superficial inguinal lymph nodes; others accompany the small saphenous vein to the popliteal nodes. Superficial lymph vessels of the gluteal region circle anteriorly to the proximal superficial inguinal nodes.

Lymphatic drainage of deeper tissues in lower limbs

The deep vessels accompany the main blood vessels: anterior and posterior tibial, peroneal, popliteal and femoral. The deep vessels from the foot and leg are interrupted by popliteal nodes; those from the thigh pass to the deep inguinal nodes.

The deep lymph vessels of the gluteal and ischial regions follow their corresponding blood vessels. Those with the former end in a node near the intrapelvic part of the superior gluteal artery, near the superior border of the greater sciatic foramen; those which follow the inferior gluteal vessels traverse one or two of the small nodes below the piriformis and pass to the internal iliac nodes.

DRAINAGE

Lymph from most of the abdominal wall and all abdominal viscera (except a small hepatic region) is returned via the thoracic duct. Lymphatic vessels run with their corresponding arteries, the lymphatic nodes forming a large number of intermediary groups along the arteries concerned and a few terminal groups near the abdominal aorta. Although referred to as illustrative examples in the introductory paragraphs, they are summarized here with numerous additions.

Lumbar nodes

The lumbar nodes include three terminal groups, each of which although interconnected has its own large area of drainage, a number
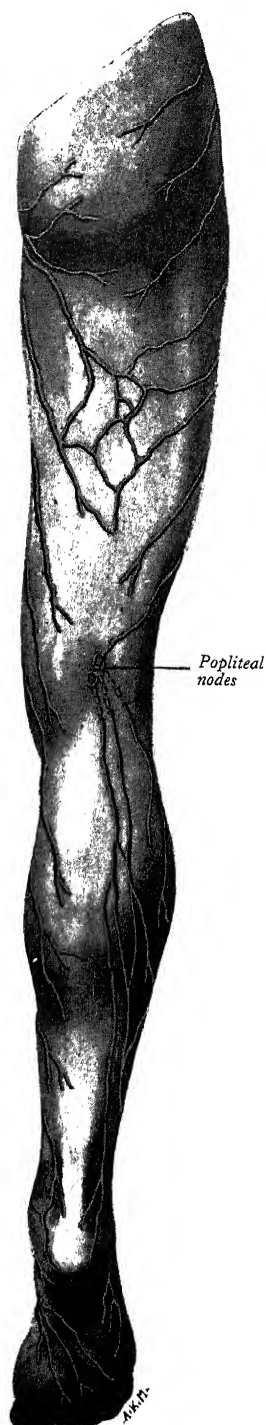
Superficial inguinal nodes (upper group)

Superficial inguinal nodes (lower group)

Great saphenous vein

10.194A The lymphatic drainage of the superficial tissues of the lower limb: anteromedial aspect (semi-diagrammatic).


Popliteal nodes

B

10.194B The lymphatic drainage of the superficial tissues of the lower limb: posterior aspect (semi-diagrammatic).

of intermediary groups and one 'subsidiary' group (**10.196, 197**). These groups are pre-aortic, lateral aortic (right and left) and retro-aortic.

The pre-aortic group. It drains viscera supplied by the ventral splanchnic aortic branches, i.e. the abdominal part of the alimentary canal (down to midrectum) and its derivatives.

The lateral aortic groups. They drain viscera and other structures supplied by the lateral splanchnic and dorsolateral somatic aortic branches, receiving efferents from the large intermediary groups associated with the iliac vessels; their upper members are therefore

terminal groups for suprarenal glands, kidneys, ureters, testes, ovaries, pelvic viscera (apart from the gut) and the deeper tissues of the posterior abdominal wall, the full thickness of the subumbilical abdominal, pelvic and perineal walls and the whole of the lower limbs.

The retroaortic group. This has no special area of drainage; though it may have been primarily associated with drainage of the posterior abdominal wall, it may be regarded as comprising peripheral nodes of the lateral aortic groups and interconnecting surrounding groups.

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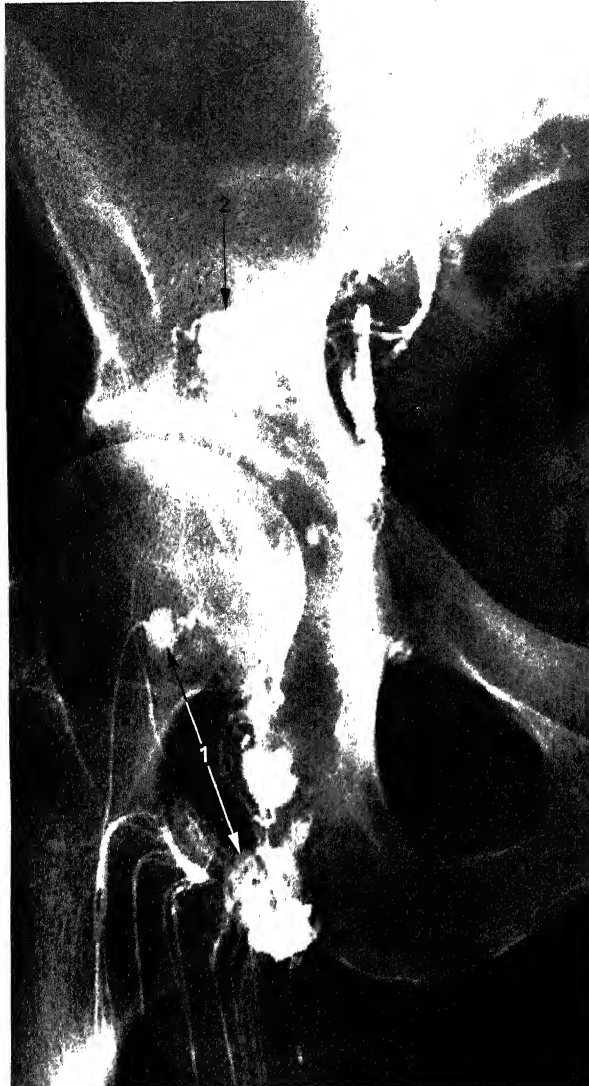
10.195 Lymphangiogram showing the inguinal lymph vessels and nodes taken immediately following injection of ultrafluid lipiodol into a lymph vessel on the dorsum of the foot. 1. Inguinal lymph nodes. 2. External iliac lymph node. (Supplied by J B Kinmonth.)

Lateral aortic nodes

node

Common iliac nodes

External iliac nodes
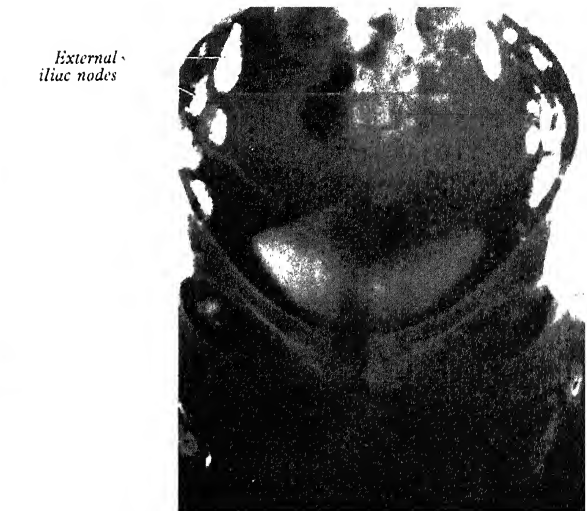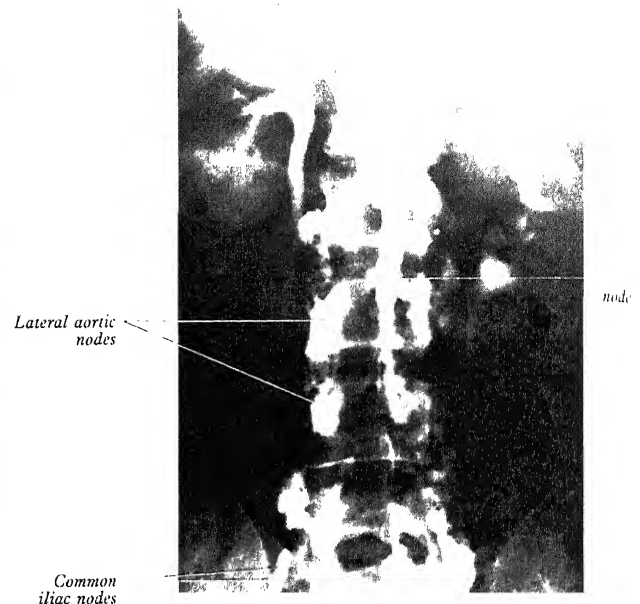
10.196 Lymphangiogram showing the lateral aortic and proximal iliac lymph nodes, approximately 24 hours after the injection of lipiodol into a lymphatic vessel on the dorsum of each foot. Intravenous contrast was given to show the kidneys and ureters. (Supplied and photographed as in 10.191.)

PRE-AORTIC LYMPH NODES

Pre-aortic lymph nodes are anterior to the abdominal aorta; they receive lymph from the regional nodes associated with the subdiaphragmatic part of the alimentary canal, pancreas, liver and spleen. Their cranial efferents form intestinal trunks entering the abdominal confluence of lymph trunks (p. 839). They are divisible into coeliac, superior mesenteric and inferior mesenteric groups, being near the origins of these arteries.

In the alimentary canal, lymph vessels begin as minute subepithelial radicles, blind at one end and opening into a *periglandular plexus*. In the small intestine each villus has a central vessel, known as a *lacteal* from its milky appearance. From the periglandular plexuses vessels pierce the muscularis mucosae to join a submucosal plexus, efferents from which traverse the muscularis, where they connect with or bypass the vessels draining it. The submucosal plexus is also joined by vessels from the lymph spaces at the bases of solitary

lymphatic follicles. Lymphatics of intestinal muscle drain into a plexus mainly between the longitudinal and circular layers. Collecting vessels leave the gut through the muscle to enter the larger vessels following their mesenteric arteries. Collecting vessels from the alimentary canal pass through local nodes before reaching the pre-aortic group.

Coeliac nodes

Coeliac nodes lie anterior to the abdominal aorta around the origin of the coeliac artery. They are a terminal group, their efferents forming right and left intestinal lymph trunks. Their afferents are from the regional nodes along branches of the coeliac artery, forming three main groups: gastric, hepatic and pancreaticosplenic; and they also come from the lower pre-aortic groups.

Gastric nodes (10.198, 199). They comprise the left gastric, right gastro-epiploic and pyloric groups. *Left gastric nodes*, along the left gastric artery, are divisible into subgroups: **superior** on the artery's

...em and **inferior** with descending branches along the cardiac half of the lesser curvature in the lesser omentum and paracardial, a chain around the cardiac orifice. They receive lymph both from the stomach and the abdominal part of the oesophagus; their efferents pass to the coeliac group of pre-aortic nodes. *Right gastro-epiploic lymph nodes*, four to seven, lying in the greater omentum along the pyloric half of the greater curvature, receive afferents from the stomach; their efferents mostly pass to the *pyloric* nodes. Four or five pyloric lymph nodes are near the gastroduodenal artery's bifurcation, in the angle between the superior and the descending parts of the duodenum; an outlying node is sometimes sited above the duodenum near the right gastric artery. These nodes drain the pyloric part of the stomach, the first part of the duodenum and finally the right gastro-epiploic nodes; their efferents end in coeliac nodes.

Hepatic nodes (10.198). These extend in the lesser omentum along the hepatic arteries and bile duct. They vary in number and site but almost constant are: one at the junction of the cystic and common hepatic ducts, the cystic node; and another alongside the upper bile duct, the node of the anterior border of the epiploic foramen. Hepatic nodes drain the stomach, duodenum, liver, gallbladder, bile ducts and pancreas; they drain to the coeliac nodes and thence to the intestinal trunks. Enlarged hepatic nodes may press on and obstruct the portal vein.

Pancreaticosplenic nodes (10.199). They accompany the splenic artery, near the posterior surface and superior border of the pancreas; one or two are in the gastrosplenic ligament. Their afferents are from the stomach, spleen and pancreas; their afferents join the coeliac nodes.

Lymphatic drainage of stomach and duodenum. Gastric lymphatics (10.198, 199) are continuous at the cardiac orifice with the oesophageal vessels and at the pylorus with the duodenal channels. They largely follow blood vessels and form four groups: vessels of the first group accompany branches of the left gastric artery, receive from a large area on both gastric surfaces and end in the left gastric lymph nodes; a second group drains the gastric fundus and body left of a vertical from the oesophagus, accompanying the short gastric and left gastro-epiploic vessels to end in the pancreaticosplenic nodes; the third group drains the right half of the greater curvature as far as the pylorus, ending in the right gastro-epiploic nodes which drain to pyloric nodes; the fourth group drains the pyloric part of the stomach and drains to the hepatic, pyloric and left gastric nodes. Although these vessels communicate, their valves direct lymph from the right part of the stomach to the lesser curvature and from the left part to the greater curvature.

Duodenal lymphatics run anteriorly and posteriorly into the small pyloric lymph nodes, lying in the anterior and posterior grooves between the pancreatic head and the duodenum. They drain up to the hepatic and down to the pre-aortic nodes around the origin of the superior mesenteric artery.

Lymphatic drainage of liver. Hepatic collecting vessels are divisible into superficial and deep systems.

Superficial hepatic vessels. These run in subserosal areolar tissue over the whole surface of the organ, draining in four directions:

(1) From the middle part of its posterior surface, the caudate lobe, the posterior part of the convex surfaces of both lobes near the hepatic attachment of the falciform ligament, the posterior part of the inferior surface of the right lobe, vessels accompany the inferior vena cava to nodes around its terminal part. Vessels in the coronary and right triangular ligaments may directly enter the thoracic duct without any intervening node.

(2) Vessels from the rest of the inferior surface and anterior part of the convex surfaces of both lobes near the attachment of the falciform ligament all converge to the porta hepatis to end in the hepatic nodes.

(3) From the posterior region of the left lobe a few vessels pass towards the oesophageal opening to end in the paracardial nodes.

(4) From the remaining convex surface of the right lobe one or two trunks accompany the inferior phrenic artery across the right crus to the coeliac nodes.

Deep hepatic lymphatics. They form the ascending and descending trunks; the ascending trunks accompany the hepatic veins and pass through the vena caval opening to end in the nodes round the end


Lateral aortic nodes

External iliac nodes

Superficial inguinal nodes
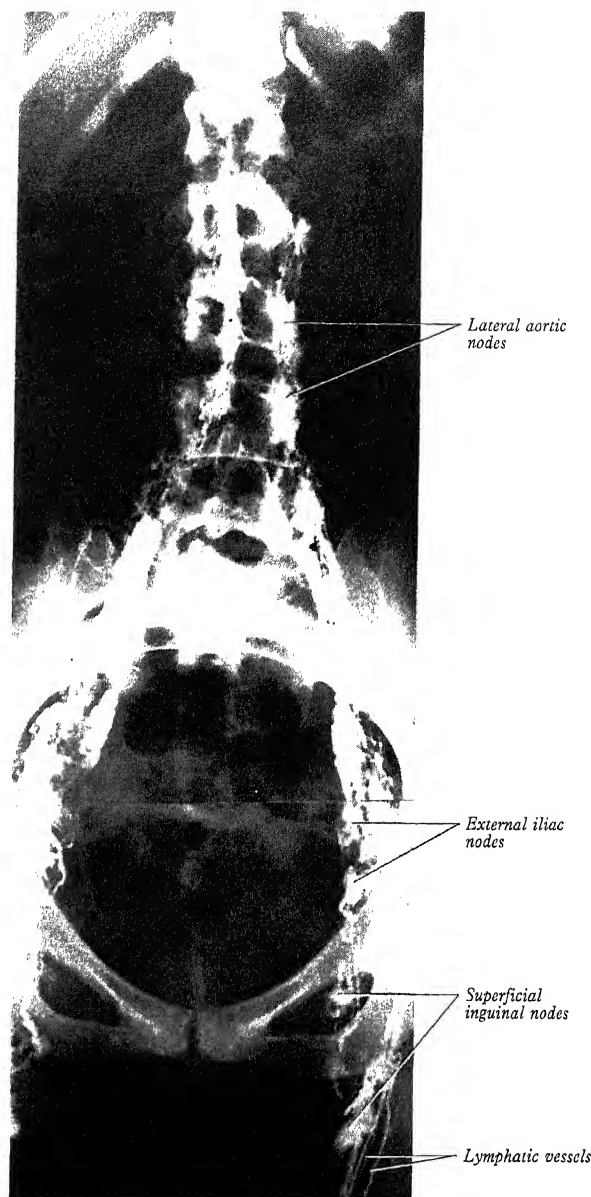
Lymphatic vessels

10.197 Lymphangiogram showing the lymphatic vessels and nodes of the iliac and lateral aortic regions taken approximately 3 hours after the injection of lipiodol into a lymphatic vessel on the dorsum of each foot. (Supplied by G I Verney, Addenbrooke's Hospital, Cambridge; photographs prepared by Sarah Smith and K Fitzpatrick, Guy's Hospital.)

of the inferior vena cava; the descending trunks emerge from the porta hepatis to end in the hepatic nodes (p. 1802).

Lymphatic drainage of gallbladder and bile ducts. Numerous vessels run from the submucosal and subserosal plexuses on all aspects of the gallbladder and cystic duct, those on the former's hepatic aspect connecting sparsely with the hepatic vessels. They pass to the hepatic nodes, especially the cystic node and node of the anterior epiploic border (see above). Hepatic nodes also collect from vessels accompanying the hepatic ducts and the upper part of the bile duct, those of its lower part draining into the inferior hepatic and upper pancreaticosplenic nodes.

Lymphatic drainage of pancreas. Lymph capillaries commence around the acini and their continuations, following the blood vessels; there are no lymphatics in the pancreatic islets. Most vessels end in the pancreaticosplenic nodes, some in nodes along the pancreaticoduodenal vessels and others in the superior mesenteric pre-aortic nodes.
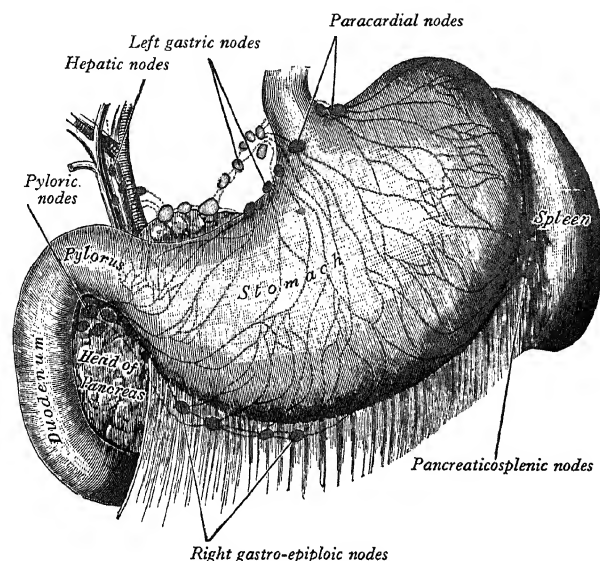
10.198 The lymphatic drainage of the stomach and duodenum. (After Jamieson & Dobson.)

Lymphatic drainage of spleen. Collecting vessels from the capsule end in the pancreaticosplenic lymph nodes.

Superior and inferior mesenteric nodes

Located anterior to the aorta near the origins of these arteries, the superior and inferior mesenteric nodes are preterminal groups for the alimentary canal from the duodenojejunal flexure to the upper anal canal and collect from outlying groups, including the mesenteric,
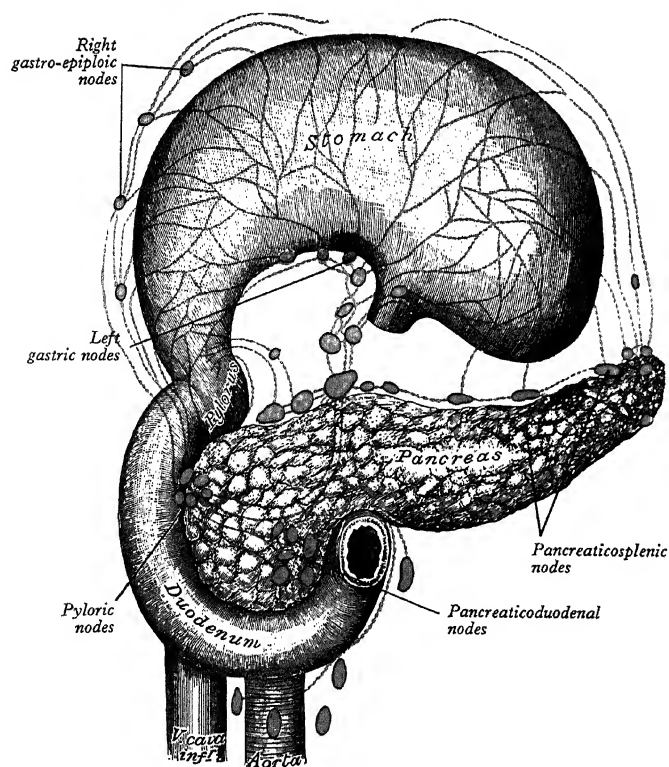
ileocolic, colonic and pararectal nodes. They discharge into the coeliac nodes and thence intestinal trunks, confluence and thoracic duct.

Mesenteric nodes. Numbering 100–150, the mesenteric nodes comprise three series: one close to the intestinal wall among the terminal rami of the jejunal and ileal arteries (mural); a second is among the loops and primary branches of the vessels (intermediate); and a third is along the upper trunk of the superior mesenteric artery (juxta-arterial). Vessels from the terminal centimetres of the ileum follow the ileal branch of the ileocolic artery to the ileocolic nodes.

Clinical anatomy. Enlargement of the mesenteric nodes occurs in many intestinal diseases, especially typhoid fever, tuberculous ulceration and malignant tumours. Enlarged nodes can often be palpated through the abdominal wall.

Ileocolic nodes (10.200, 201). They form a chain of 10–20 around the ileocolic artery but tend to form two groups: near the duodenum and along the artery's terminal part. The chain divides with the artery, into:

- *ileal nodes* close to the ileal branch;
- *anterior ileocolic nodes* (usually 3) in the ileocaecal fold, near the caecal wall;
- *posterior ileocolic nodes*, mostly in the angle between ileum and colon but partly behind the caecum at its junction with the ascending colon;
- an *appendicular node* in the mesoappendix.

Colic nodes. They form four groups: epicolic, paracolic, intermediate colic and preterminal colic.
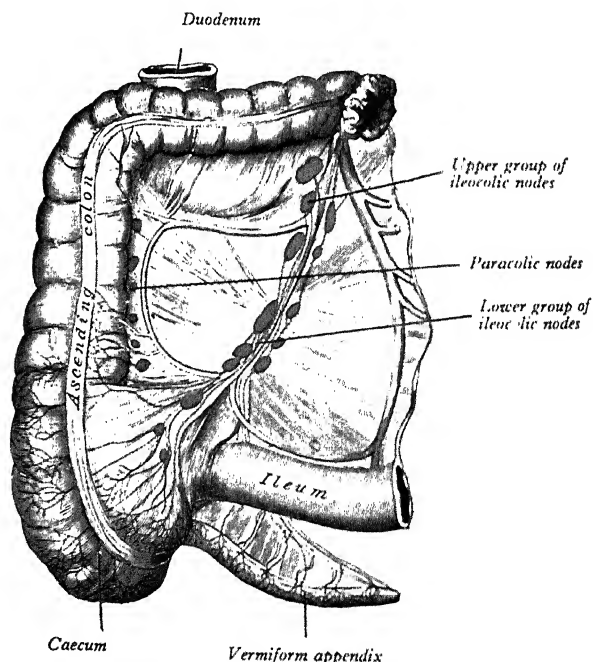
Epicolic nodes. They are merely minute nodules on the colonic wall, sometimes in the appendices epiploicae.

Paracolic nodes. These lie along the medial borders of the ascending and descending colon and along the mesenteric borders of the transverse and sigmoid colon.

Intermediate colic nodes. They lie along the right, middle and left colic arteries.

Preterminal colic nodes. Adjoining the main trunks of the superior and inferior mesenteric arteries, they are near their corresponding pre-aortic nodes.

Pararectal nodes. These nodes, in contact with the rectal muscular wall, drain to an intermediate group around the superior rectal artery and thence to nodes near the origin of the inferior mesenteric. Others drain to nodes at the bifurcation of the common iliac artery.

10.199 The lymph vessels and nodes of the stomach, duodenum and pancreas. The stomach has been turned upwards. (After Jamieson & Dobson.)

10.200 The lymph vessels and nodes of the caecum and vermiform appendix: anterior aspect. (After Jamieson & Dobson.)
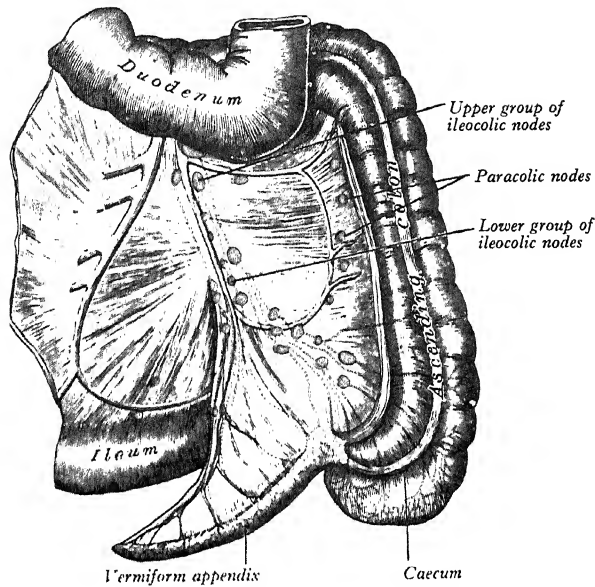
10.201 The lymph vessels and nodes of the caecum and vermiform appendix: posterior aspect. (After Jamieson & Dobson.)

Lymphatic drainage of jejunum and ileum. Lacteals pass between layers of the mesentery but, before reaching the superior mesenteric nodes, the lymph traverses the mesenteric nodes.

Lymphatic drainage of vermiform appendix and caecum (10.200, 201). Lymphatic vessels are numerous, since lymphoid tissue abounds in their walls. From the body and apex of the appendix 8–15 vessels ascend in the mesoappendix, a few interrupted by one or more nodes in it. They unite to form three or four larger vessels, ending in the inferior and superior nodes of the ileocolic chain.

Vessels from the root of the appendix and caecum are anterior and posterior. Anterior vessels pass in front of the caecum to the anterior ileocolic nodes and nodes of the ileocolic chain; posterior vessels ascend behind the caecum to the posterior and inferior ileocolic nodes.

Lymphatic drainage of colon (10.200–203). Lymphatic vessels of ascending and transverse parts of the colon end in the superior mesenteric nodes, after traversing nodes along the right and middle colic arteries and their branches. Those of the descending and sigmoid parts are interrupted by small nodes on branches of the left colic arteries, ending in the pre-aortic nodes around the origin of the inferior mesenteric artery.

Lymphatic drainage of rectum and anal canal. From the upper half, or more, of the rectum vessels emerge from its wall to ascend with the superior rectal vessels through the pararectal nodes to nodes in the lower sigmoid mesocolon and along the inferior mesenteric artery. From the lower half of the rectum and the anal canal, above its mucocutaneous junction, lymph vessels ascend through the wall to accompany the middle rectal vessels to the internal iliac nodes. Some are said to traverse the levator ani into the ischiorectal fossa, to accompany the inferior rectal and internal pudendal vessels to the internal iliac nodes. Lymphatics of the anal canal below the mucocutaneous junction descend to the anal margin, curving laterally to reach the most medial superficial inguinal nodes.

LATERAL AORTIC NODES

The lateral aortic nodes flank the abdominal aorta anterior to the medial margins of the psoas major muscles, diaphragmatic crura and sympathetic trunks (10.196, 197). On the right, some are lateral to the inferior vena cava and anterior to it near the end of the right renal vein. Afferents reach these nodes from structures supplied by the lateral splanchnic and dorsolateral somatic aortic branches and from outlying nodes near the iliac arteries and their branches. Efferents form a *lumbar trunk* on each side, both terminating in the confluence of lymph trunks (occasionally a cisterna chyli, p. 1610); a few may pass to the pre-aortic and retro-aortic nodes. Some of the efferents of the right lumbar lymph trunk and its nodes may
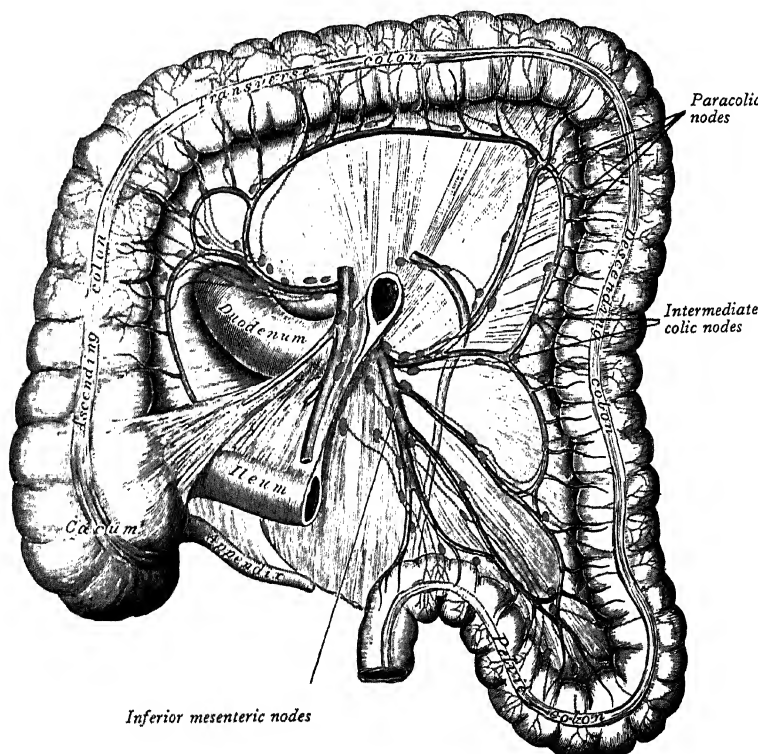
10.202 The lymph vessels and nodes of the colon. (After Jamieson & Dobson.)
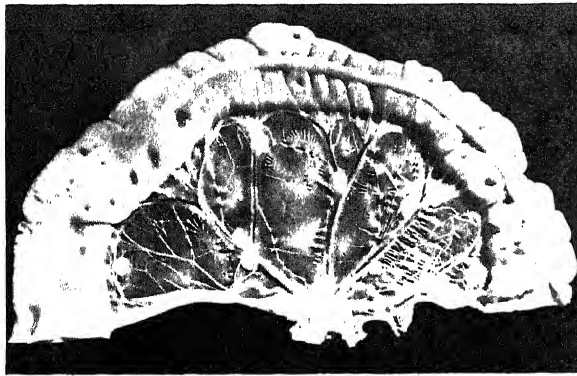
10.203 Preparation of the human colon and mesocolon displaying arterial arcades, neurovascular bundles, lymphatics and paracolic and intermediate lymph nodes. (Provided by S Kubic, University of Zürich.)

cross to their left counterparts; or both trunks may divide forming a loose plexus.

Lymphatic vessels from the kidney, suprarenal gland, abdominal ureter, posterior abdominal wall, testis and ovary, uterine tube and upper part of the uterus all pass directly to the lateral aortic nodes. Lymphatics from the pelvis, most pelvic viscera and the anterolateral abdominal wall pass first to regional nodes largely related to the internal iliac arteries and their branches. These include the following groups: common, external, internal and circumflex iliac, inferior epigastric and sacral. It must also be emphasized that the external iliac group receives the efferents from the inguinal nodes and the internal iliac group receives deep gluteal lymph; thus the lateral aortic groups ultimately drain the whole of both lower limbs.

Common iliac nodes. The 4–6 nodes are grouped around the artery, one or two inferior to the aortic bifurcation and anterior to the fifth lumbar vertebra or sacral promontory (10.204). They drain the external and internal iliac nodes and send efferents to the lateral aortic nodes. They are usually in medial, lateral and intermediate (anterior) chains, the lateral being the main route.

External iliac nodes (10.196, 197, 204). These 8–10 nodes usually form three subgroups, lateral, medial and anterior to the external iliac vessels; the anterior is inconstant. The medial nodes are considered the main channel of drainage, collecting from: the *inguinal nodes* (p. 1615), the deeper layers of the infra-umbilical abdominal wall, the adductor region of the thigh, the glans penis or clitoris, the membranous urethra, prostate, vesical fundus, cervix uteri and upper vagina. Their efferents pass to the common iliac nodes.

Inferior epigastric and circumflex iliac nodes. They are associated with their vessels and drain the corresponding areas, being outlying members of the external iliac group and inconstant in number.

Internal iliac nodes (10.204–206). Surrounding the vessels, they receive afferents from all the pelvic viscera, deeper parts of the perineum and gluteal and posterior femoral muscles. Efferents pass to the common iliac nodes.
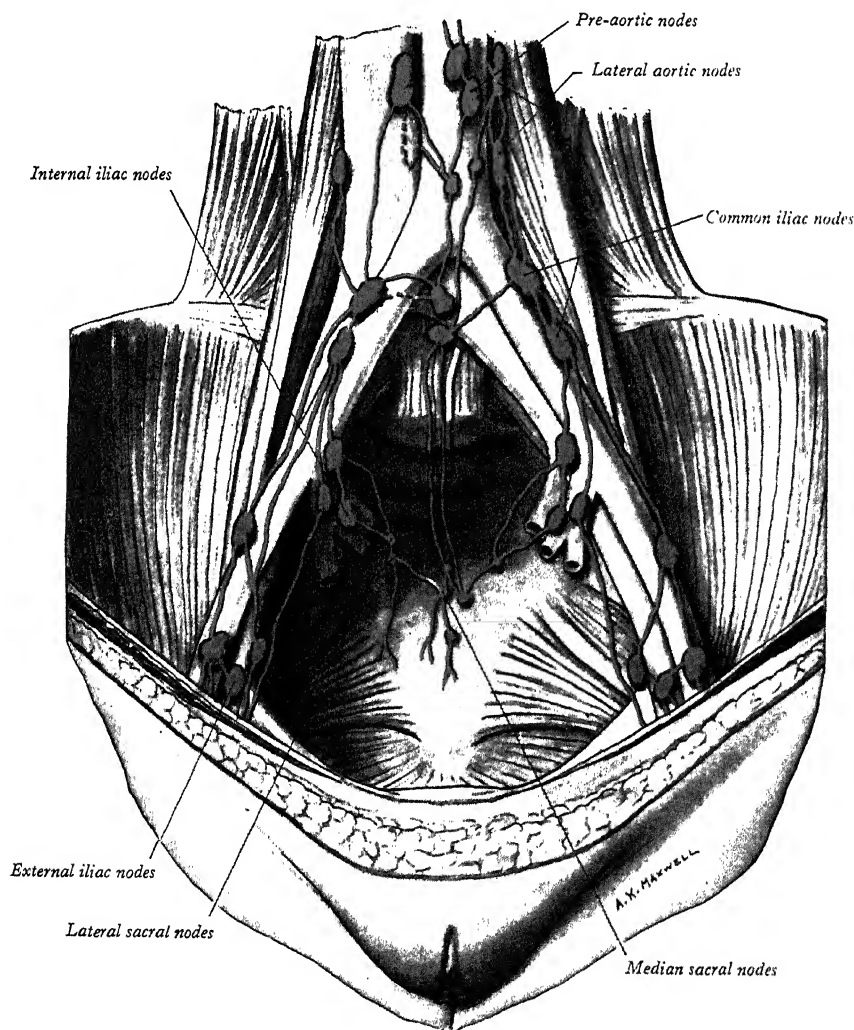
Sacral nodes. Found along the median and lateral sacral vessels and an obturator node, sometimes occurring in the obturator canal, they are outlying members of the internal iliac group. There is considerable bypassing in the iliac groups of lymph nodes. Lymphangiographic studies have demonstrated the connections between the right and left groups.

Lymphatic drainage of urinary tract

Renal. Renal lymphatic vessels begin in three plexuses: one around the renal tubules, a second under the renal capsule and a third in the perirenal fat connecting freely with the second plexus. Collecting vessels from the intrarenal plexus form four or five trunks following the renal vein to end in the lateral aortic nodes; as they leave the hilum they are joined by the subcapsular collecting vessels. The perirenal plexus drains directly into the same nodes.

Ureteric. Vessels begin in submucosal, intramuscular and adventitial plexuses which intercommunicate. Collecting vessels from the upper ureter may join the renal collecting vessels or pass directly to the lateral aortic nodes near the origin of the gonadal artery; those from its lower abdominal part go to the common iliac nodes; those from its pelvic part end in the common, external or internal iliac nodes.

Vesical. Lymphatics (10.205) begin in the mucosal, intermuscular and serosal plexuses. Collecting vessels, nearly all ending in the external iliac nodes, are in three sets:

- vessels from the trigone emerge on the vesical exterior to run superolaterally;
- those from the superior surface converge to the posterolateral angle and pass superolaterally across the lateral umbilical ligament to the external iliac nodes (one may go to the internal or common iliac group);
- those from the inferolateral surface ascend to join those from the superior surface.

Minute nodules of lymphoid tissue may occur along the vesical lymph vessels.

Urethral. These are of two sorts:

- Vessels from the prostatic and membranous urethra in males and the whole female urethra pass mainly to the internal iliac nodes; a few may end in the external iliac nodes. Vessels from the membranous urethra accompany the internal pudendal artery.
- Vessels of the male spongiose urethra accompany those of the glans penis, ending in the deep inguinal nodes. Some may end in superficial nodes, others may traverse the inguinal canal to the external iliac nodes.

Lymphatic drainage of male reproductive organs

Testis. Testicular vessels commence in a superficial plexus, under the tunica vaginalis, and a deep plexus in the substance of the testis and the epididymis. Four to eight collecting trunks ascend in the spermatic cord and accompany the testicular vessels on the psoas major, ending in the lateral aortic and pre-aortic nodes.

Ductus deferens, seminal vesicle and prostate gland. Collecting vessels from the ductus end in the external iliac nodes, while those from the seminal vesicle go to the internal and external iliac nodes. Prostatic vessels end mainly in internal iliac and sacral nodes; a vessel from the posterior surface accompanies the vesical vessels to the external iliac nodes and one from the anterior surface gains the internal iliac group by joining vessels of the membranous urethra.

Scrotum and penis. The skin of these parts is drained by vessels which, with those of all perineal skin, accompany the external pudendal blood vessels to the superficial inguinal nodes. Lymph vessels of the glans penis pass to the deep inguinal and external iliac nodes, from the erectile tissue and penile urethra to the internal iliac lymph nodes.
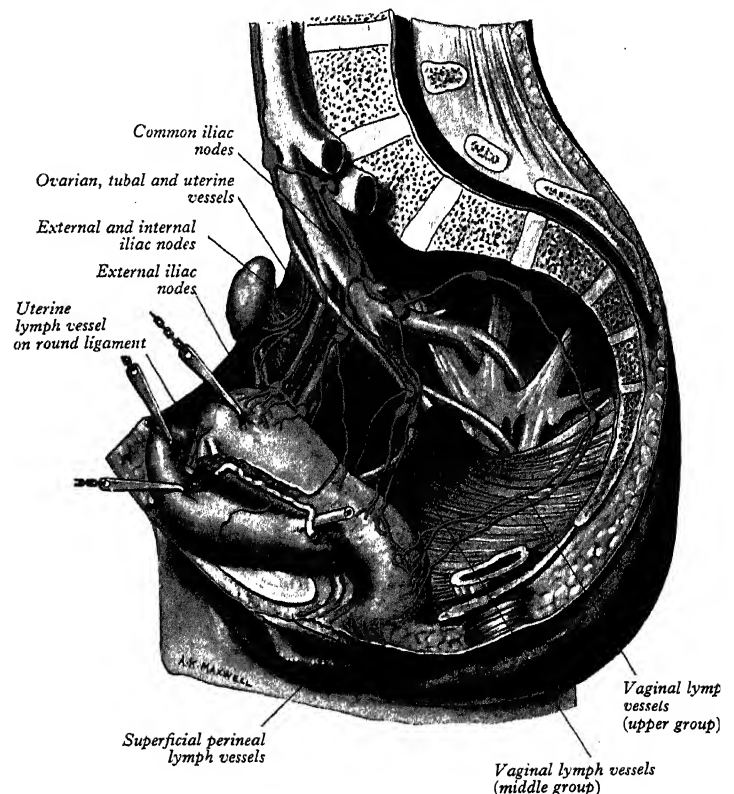
Lymphatic drainage of female reproductive organs
(10.206)

Ovary. The vessels, like the testicular, ascend along the ovarian artery to the lateral aortic and pre-aortic nodes.

Uterus and uterine tube. Uterine lymphatics are superficial (or subperitoneal) and deep in the uterine wall. Collecting vessels from the cervix pass laterally in the parametrium to the external iliac
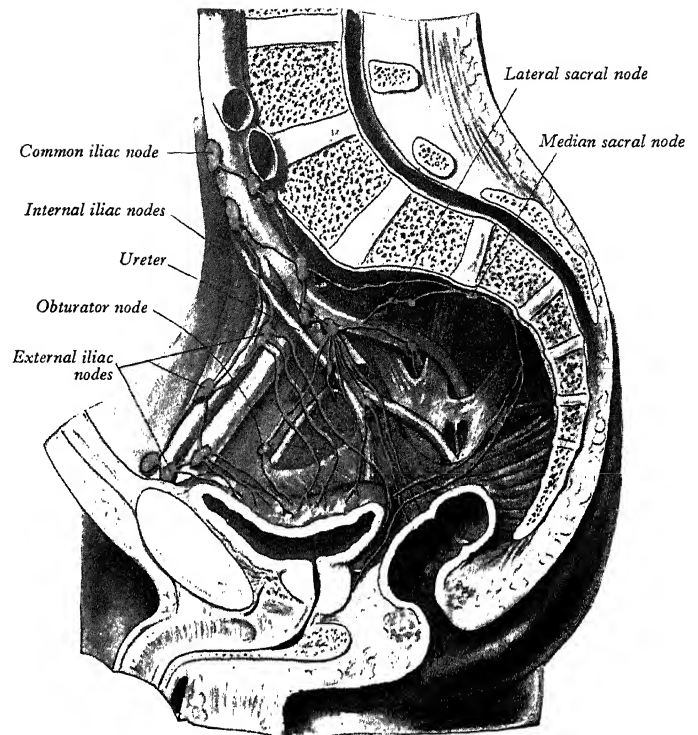
10.205 The lymphatic drainage of the urinary bladder (semi-diagrammatic).

10.206 The lymphatic drainage of the female reproductive organs (semi-diagrammatic). (After Cunéo & Marcille.)

1623

nodes, posterolaterally to the internal iliac nodes and posteriorly in the sacrogenital fold to the rectal and sacral nodes. Some cervical efferents may reach the obturator or gluteal nodes. Vessels from the lower part of the uterine body pass mostly to the external iliac nodes, with those from the cervix. From the upper part of the body, the fundus and the uterine tubes, vessels accompany those of the ovaries to the lateral aortic and pre-aortic nodes, a few passing to the external iliac nodes. The region surrounding the isthmic part of the uterine tube is drained along the round ligament to the superficial inguinal nodes. Uterine lymph vessels enlarge greatly during pregnancy.

Vagina. Vaginal lymphatic vessels link with those of the cervix uteri, rectum and vulva. They form three groups but the regions drained are not sharply demarcated. Upper vessels accompany the uterine artery to the internal and external iliac nodes, intermediate vessels accompany the vaginal artery to the internal iliac nodes; vaginal vessels below the hymen, from the vulva and perineal skin, pass to the superficial inguinal nodes but the clitoris and labia minora drain to the deep inguinal nodes and direct clitoridial efferents may pass to the internal iliac nodes (Kubik 1967).

Lymphatic drainage of abdominal wall

The lymphatic vessels here are either superficial or deep to the deep fascia.

Superficial vessels. These accompany the subcutaneous blood vessels. Lumbar and gluteal vessels run with the superficial circumflex iliac vessels, those from the infra-umbilical skin with the superficial epigastric vessels. Both drain into the superficial inguinal nodes. The supra-umbilical region is drained by vessels running obliquely up to the pectoral and subscapular axillary nodes, a few to the parasternal nodes.

Deep vessels. They accompany the deep arteries, the posterior passing without interruption with the lumbar arteries to the lateral aortic and retro-aortic nodes; those from the upper anterior abdominal wall run with the superior epigastric vessels to the parasternal nodes; those of its lower part end in the circumflex iliac, inferior epigastric and external iliac nodes. Vessels of the pelvic wall follow the internal iliac artery and its parietal branches to end in the iliac or lateral aortic nodes.

LYMPHATIC DRAINAGE OF THORAX

LYMPHATIC DRAINAGE OF THORACIC WALLS

Superficial lymphatic vessels of the thoracic wall ramify subcutaneously and converge on the axillary nodes. Those superficial to the trapezius and latissimus dorsi unite to form 10 or 12 trunks ending in the subscapular nodes. Those in the pectoral region, including vessels from the skin covering the periphery of the mammary gland and its subareolar plexus, run back, collecting those superficial to serratus anterior, to reach the pectoral nodes. Vessels near the lateral sternal margin pass between the costal cartilages to the parasternal nodes but also anastomose across the sternum. A few vessels from the upper pectoral region ascend over the clavicle to the inferior deep cervical nodes. Lymph vessels from deeper tissues of the thoracic walls drain mainly to the parasternal, intercostal and diaphragmatic lymphatic nodes.

Parasternal (internal thoracic) nodes. Four or five on each side, they are at the anterior ends of the intercostal spaces, along each internal thoracic artery. They drain afferents from the mammary gland, deeper structures of the supra-umbilical anterior abdominal wall, the superior hepatic surface through a small group of nodes behind the xiphoid process and deeper parts of the anterior thoracic wall. Their efferents usually unite with those from the tracheobronchial and brachiocephalic nodes to form the bronchomediastinal trunk; this may open, on either side, directly into the jugulosubclavian junction into either great vein near the junction or may join the right subclavian trunk, the right lymphatic duct or, on the left, the thoracic duct.

Intercostal nodes. These occupy the intercostal spaces near the heads and necks of the ribs. They receive deep lymph vessels from the posterolateral aspects of the chest and the mammary gland; some are interrupted by small lateral intercostal nodes. Efferents of nodes

in the lower four to seven spaces unite into a trunk descending to the abdominal confluence of lymph trunks or to the commencement of the thoracic duct (p. 1610). Efferents of nodes in the left upper spaces end in the thoracic duct, those of the right upper spaces end in one of the right lymph trunks.

Diaphragmatic nodes. Located on the thoracic surface of the diaphragm, they comprise: anterior, right and left lateral and posterior groups.

The anterior group. This consists of two or three small nodes behind the base of the xiphoid process, draining the convex hepatic surface, and one or two nodes on each side near the junction of the seventh rib and cartilage, which receive anterior lymph vessels from the diaphragm. The anterior group drains to the parasternal nodes.

The lateral groups. They each contain two or three nodes, close to the entry of the phrenic nerves into the diaphragm. On the right some nodes lie within the fibrous pericardium anterior to the intrathoracic end of the inferior vena cava. Their afferents are from the central diaphragm, the right also draining the convex surface of the liver. Their efferents pass to the posterior mediastinal, parasternal and brachiocephalic nodes.

The posterior group. It contains a few nodes on the back of the crura, connected with the lateral aortic and posterior mediastinal nodes.

Lymphatic drainage of deeper tissues

Collecting vessels of the deeper thoracic tissues include the following:

- Lymphatics of muscles attached to the ribs: most end in axillary nodes, some from pectoralis major in the parasternal nodes.
- Intercostal vessels draining the intercostal muscles and parietal pleura; those from the anterior thoracic wall and pleura end in the parasternal nodes, the posterior in intercostal nodes.
- Vessels of the diaphragm form two plexuses, thoracic and abdominal, anastomosing freely and best marked in areas covered respectively by pleurae and peritoneum. The thoracic plexus unites with lymph vessels of the costal and mediastinal pleura, its efferents being: *anterior*, passing to the anterior diaphragmatic nodes near the junctions of the seventh ribs and cartilages; *middle*, to nodes on the oesophagus and around the end of the inferior vena cava; *posterior*, to nodes around the aorta where it leaves the thorax. The abdominal plexus anastomoses with the hepatic lymphatics and peripherally with those of the subperitoneal tissue. Efferents from its right half end partly in a group of nodes on the inferior phrenic artery, others in the right lateral aortic nodes. Those from the left half of the abdominal diaphragmatic plexus pass to the pre-aortic and lateral aortic nodes and nodes near the terminal oesophagus.
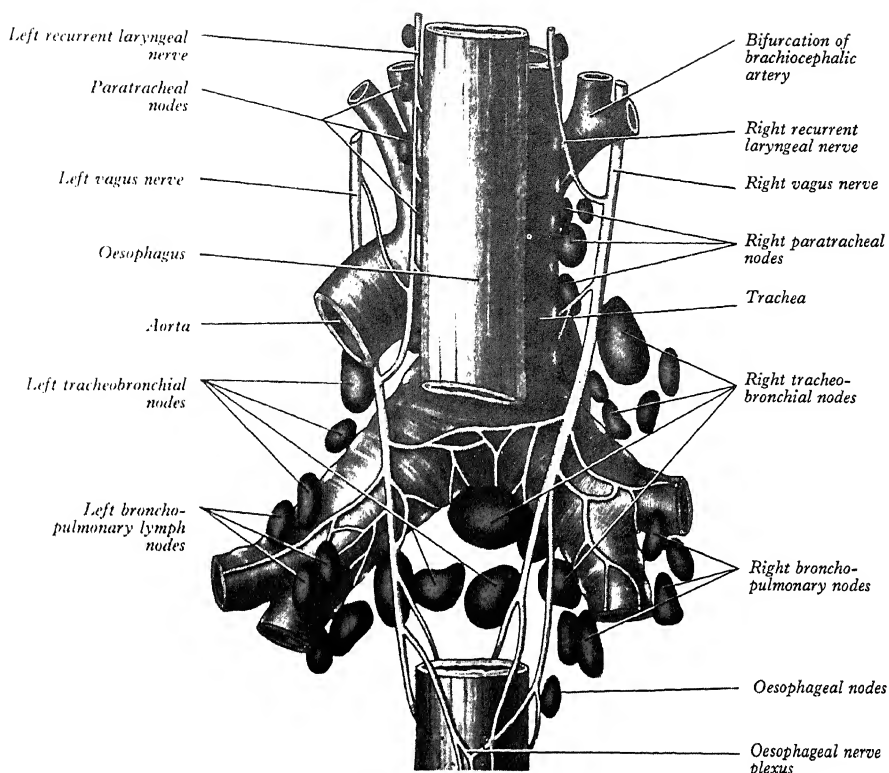
LYMPHATIC DRAINAGE OF THORACIC CONTENTS

Lymph from thoracic viscera traverses one or other of three groups of nodes, brachiocephalic, posterior mediastinal or tracheobronchial, before entering the thoracic duct, the right lymphatic duct or some other lymph trunk entering one of the great veins at the root of the neck.

Brachiocephalic nodes. These are in the superior mediastinum, anterior to the brachiocephalic veins and large arterial trunks springing from the aortic arch. They drain the thymus and thyroid glands, pericardium, heart and lateral diaphragmatic nodes; their efferents unite with those of the tracheobronchial nodes to form the right and left bronchomediastinal trunks.

Posterior mediastinal nodes. Behind the pericardium, near the oesophagus and the descending thoracic aorta, their afferents are from: the oesophagus, posterior pericardium, diaphragm, lateral and posterior diaphragmatic nodes and sometimes the left lobe of the liver. They drain chiefly to the thoracic duct but some join the tracheobronchial nodes.

Tracheobronchial nodes (10.207). They are in five main groups (Naruke et al 1978), including some of the largest nodes:

- *paratracheal*, in front and to the sides of the thoracic portion of the trachea but continuous above with the cervical paratracheal nodes
- *superior tracheobronchial*, in the angles between the trachea and the bronchi

Left recurrent laryngeal nerve

Paratracheal nodes

Left vagus nerve

Oesophagus

Aorta

Left tracheobronchial nodes

Left broncho-pulmonary lymph nodes

Bifurcation of brachiocephalic artery

Right recurrent laryngeal nerve

Right vagus nerve

Right paratracheal nodes

Trachea

Right tracheo-bronchial nodes

Right broncho-pulmonary nodes

Oesophageal nodes

Oesophageal nerve plexus

10.207   The lymph nodes of the trachea, bronchi and lungs. Note the large 'carinate' node lodged between the bifurcation of the principal bronchi.

• *inferior tracheobronchial* or *subcarenal nodes*, in the angle between the bronchi
• *bronchopulmonary* or *hilar nodes*, in the hilum of each lung around the main bronchi
• *pulmonary* or *intralobar*, in the lung substance on larger branches of the principal bronchi.

These groups are not sharply demarcated; pulmonary nodes become continuous with the bronchopulmonary and they in turn with the inferior and superior tracheobronchial nodes, continuous with the paratracheal group. Afferents of tracheobronchial nodes drain the lungs and bronchi, thoracic trachea, heart and some efferents of the posterior mediastinal nodes. Their efferent vessels ascend on the trachea to unite with efferents of the parasternal and brachiocephalic nodes as the right and left bronchomediastinal trunks; the right trunk may occasionally join a right lymphatic duct or another right-sided lymph trunk and on the left the thoracic duct; but more often they open independently in or near the jugulo-subclavian junction on their own side.

Clinical anatomy. In all town dwellers large quantities of dust and carbonaceous pigment may be freely inhaled and are continually swept into these nodes from the bronchi and alveoli. The involvement of intrathoracic lymph nodes by deposits from primary lung cancer is of major prognostic significance. Naruke et al (1978) have produced a lymph node map of the intrathoracic nodes which forms the basis of nodal staging in the tumour node metastasis (TNM) classification of lung cancer and is accepted by oncologists worldwide. They group the nodes into three: intrapulmonary, hilar and mediastinal. The prognosis when mediastinal nodes are involved is much worse than when the other two groups are involved.

Lymphatic drainage of heart

Cardiac lymphatic vessels form subendocardial, myocardial and subepicardial plexuses, the first two draining into the third, efferents of which form the left and right cardiac collecting trunks. Two or three left trunks ascend the anterior interventricular sulcus, receiving vessels from both ventricles; reaching the coronary sulcus, they are joined by a large vessel from the diaphragmatic surface of the left ventricle, which first ascends in the posterior interventricular sulcus and then turns left along the coronary sulcus. The vessel formed by the union of these two ascends between the pulmonary artery and the left atrium, usually ending in an inferior tracheobronchial node. The right trunk receives afferents from the right atrium and right border and diaphragmatic surface of the right ventricle. It ascends in the coronary sulcus, near the right coronary artery, and then anterior to the ascending aorta to end in a brachiocephalic node, usually on the left.

Lymphatic drainage of lungs and pleurae

Pulmonary lymphatic vessels originate in a superficial subpleural plexus and a deep plexus accompanies the branches of pulmonary vessels and bronchi. In larger bronchi the deep plexus has submucosal and peribronchial parts; in smaller bronchi a single plexus extends to the bronchioles but not to the alveoli, whose walls have no lymphatic vessels. Superficial efferents turn round borders and the margins of fissures to converge in the bronchopulmonary nodes; deep efferents reach the hilum along the pulmonary vessels and bronchi, ending mainly in the same nodes. There is little anastomosis between the superficial and deep lymphatics, except in the hilar regions. In peripheral parts of the lungs small channels connect superficial and deep lymphatic vessels, capable of dilatation to direct lymph from the deep to the superficial channels when outflow from deep vessels is obstructed by pulmonary disease. Deep in the fissures, lymphatic vessels of adjoining lobes connect; hence, though there is a tendency for vessels from the upper lobes to pass to the superior tracheobronchial nodes and those from lower lobes to the inferior tracheobronchial group, these connections are not exclusive. At the level of pulmonary lobation the arrangement of lymphatic vessels follows with the central artery of a lobule and its peripheral veins (Kubik 1970), confirming the findings of Celtis and Porter (1952). Policard (1950) has described lymphoid aggregations, non-follicular in appearance, in peribronchial sites and in 'placoid' formations adjoining pulmonary pleura.

Pleural lymphatic vessels exist in visceral and parietal layers, those of the visceral pleura draining to the superficial pulmonary efferents, forming a plexus beneath the pulmonary pleura (see above). Those of the parietal pleura end in three ways:

- those from the costal region join vessels of the internal intercostal muscles to reach the parasternal nodes;
- those of the diaphragmatic pleura form a plexus on its thoracic surface (p. 1624);
- those of the mediastinal pleura end in the posterior mediastinal nodes.

Lymphatic drainage of thymus

Thymic lymphatic vessels end in the brachiocephalic, tracheobronchial and parasternal nodes.

Lymphatic drainage of oesophagus

Efferent vessels from the cervical oesophagus drain to the deep cervical nodes, those from its thoracic part to the posterior mediastinal nodes and those from its abdominal part to the left gastric lymph nodes. Some may pass directly to the thoracic duct (p. 1610).